EVALUATION OF THE BLASTX3.5 COMPUTER MODEL FOR EXPLOSION BLAST ANALYSIS AND SITING OF UNDERGROUND MAGAZINES

by

Charles E. Joachim
U.S. Army Engineer Waterways Experiment Station
Vicksburg, MS 39180-6199

ABSTRACT

This paper presents an evaluation of the accuracy and reliability of the BLASTX3.5 computer model for making predictions of the internal airblast effects and external airblast hazard distances produced by accidental explosions in underground magazines. Comparisons are made between BLASTX3.5 calculations and test data from a selected set of large-scale non-responding magazine experiments.

INTRODUCTION

Over the several years, efforts have been made to demonstrate the performance of advanced numerical models as tools for predicting the airblast safety hazard distances (or Quantity-Distance, QD) associated with accidental explosions of the contents of underground magazines. In the U.S./Republic of Korea R&D Study for New Underground Ammunition Storage Technologies (UAST program), a survey was made in 1993 of the available first-principle hydrocodes to determine which would be most suitable and reliable for predicting airblast effects from detonations in underground magazines. The two most promising codes were HULL and SHARC (Joachim 94-1). Since SHARC was found to have significant advantages for the intended applications, it was selected for further evaluation. Unfortunately, several efforts to predict the internal and external airblast environment from large-scale underground magazine detonation tests were less than completely successful. In general, SHARC predicted airblast peak pressures that were significantly higher than the measured values (by factors of two to five).

In 1994-95, attempts were made to use a less rigorous code, AUTODYNE, to make such predictions. Again, however, the predictions were less than satisfactory when compared with large-scale test data.

As the experimental program conducted by the U.S. and Republic of Korea under the UAST program progressed from small-scale to intermediate-scale testing, a relatively simple PC code called BLASTX3 (Joachim 94-2) was used to make pre-test predictions for gage ranging in the test planning process. BLASTX3.5 is the latest version of a descendent family of PC codes, whose parent was called CHAMBER. The CHAMBER-BLASTX family was developed, under a combination of contract and in-house efforts, by the U.S. Army Engineer Waterways Experiment Station. The analytic model within BLASTX3.5 was modified to include smaller time steps in the gas venting calculations in order to handle the rapid mass and energy flows associated with large confined detonations. Thus, Version 3.5 of the BLASTX code (BLASTX3.5) was specifically developed for computation of blast effects from accidental detonations in underground magazines.

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OBJECTIVE

The work described in this paper was undertaken for the DoD Explosives Safety Board. The objective of that effort was to evaluate the accuracy and reliability of the BLASTX3.5 computer model for making predictions of the internal airblast effects and external airblast hazard distances produced by accidental explosions in underground magazines.

BLASTX MODEL FOR UNDERGROUND MAGAZINES

Britt (94-2) suggests that BLASTX most efficiently models blast effects in rooms with an aspect (length-to-width) ratio of 3:1. Thus, the ammunition storage chambers were modeled as single rooms. The access drifts and tunnels were divided into similarly shaped rooms with aspect ratios as close to 3:1 as possible for computational modeling. Britt (94-2) recommends a "gas only" BLASTX calculation of the pressures internal to the underground facility from the detonation products, and using the "shock only" option to calculate external pressures beyond the portal. Shock calculations from internal detonations are recommended only for chamber loading densities less than 0.15 kg/m^3.

In a typical BLASTX model of an underground ammunition storage facility long tunnels are modeled as a series of rooms linked together by common openings, where the size of each opening is the same as the tunnel cross-section at that point. The BLASTX "gas only" computational model requires input data on the volume of each room and the area of each opening. The underground magazine model typically represents the free-field outside the portal as a very large room. If the magazine facility has multiple portals, the volume outside each portal is usually represented by a separate room. A BLASTX "shock only" calculation is performed for these large rooms, using as input the pressure field at the portal as determined from a "gas only" interior calculation.

BLASTX models explosive charges as spherical sources, and can include multiple charges in multiple rooms. The explosive charge used for this analysis was modeled as a single spherical source at the center of the chamber. Britt (94-3) recommends a gas and shock calculation in the detonation chamber for pressure prediction and gage range setting. If the aspect ratio of the explosive charge is much greater than 1:1, he recommends approximating the explosive source using an array of spherical charges. These procedures were followed in the calculations reported here.

BLASTX computer models were developed to simulate the geometries and explosive load conditions of selected large-scale experiments involving explosions in underground chambers. The tests selected for analysis and calculation are listed in Table 1. They were conducted under the following test programs:

U.S. Intermediate-Scale Tests (Table 1): The computational model for the tests at the Linchburg Mine test site consisted of 84 rooms, representing the interconnected tunnels and test chambers. Figure 1 shows the original layout of the Linchburg Mine test site (Joachim 94-1). Figure 2 shows the layout after excavation of an expansion chamber and the locations of the individual tests. The Comp B explosive charges used for these tests were located at the center of the test chambers, except for Test 1, where a single cube of Comp B was suspended at the center of the tunnel cross-section. Test parameters, including net explosive quantity and loading density, are given in Table 1.

ROK Intermediate-Scale Tests (Table 1): The ROK Intermediate-Scale experiments were conducted in five 1/8-scale tunnel/chamber facilities excavated in hard rock (layouts shown in Figure 3). The computational model for Tunnel 1 was modeled as a linked array of 23 rooms. Similarly, Tunnel 3 (with an expansion chamber) was modeled with an array of 21 rooms. BLASTX models were developed for two tests in Tunnel 4. Test 8 was conducted in the straight left hand portion of Tunnel 4, with constrictions modeled by an array of 8 rooms. An additional chamber and tunnels were excavated at the Tunnel 4 complex prior to Test 14, which was modeled with an array of 14 rooms. Finally, Test 12 in the Tunnel 5 complex is modeled by an array of 24 rooms. Explosive charges for the ROK Intermediate-Scale experiments were C-4 explosive material packed in a plywood box. Test parameters are given in Table 1.

Älvdalen KLOTZ Club Tests(Table 1): The underground test facility at Älvdalen, Sweden, consists of two chambers; one (Chamber A) aligned with the axis of the main drift and the other (Chamber B) oriented at 45^{o} to the axis of the main drift (Vretblad 1988). A BLASTX model was developed (18 rooms) for three KLOTZ Club experiments in this magazine complex; Tests 7, 8, and 9 (Figure 4). Tests 7 and 8 involved 1,000 and 5,000-kg detonation, respectively, in Chamber A. Test 9 was 5,000-kg detonation in Chamber B. All explosive charges were stacks of ammonium-nitrate/fuel oil (ANFO). Test parameters are given in Table 1.

Camp Stanley 1/3-Scale Validation Tests (Table 1): The underground storage facility at Camp Stanley, Korea is unique in that it is designed to provide protection from the accidental detonation of loaded ammunition trucks. The trucks in the full-scale facility are parked in open bays located along a horseshoe-shaped main drift with two exits. To validate QD predictions for the site, a portion of the Camp Stanley tunnel (with three parking bays) was constructed at 1/3-scale in 1990 at a test site in Colorado (Figure 5). The BLASTX model consisted of 22 rooms. The explosive charges were granular Comp B explosive in a plywood box, centered in the donor chamber (Chamber B). Test parameters are given in Table 1.

PROPOSED DDESB FORMULA

The Joint U.S./Republic of Korea (ROK) UAST Program produced a large quantity of high-quality data on the airblast effects of underground detonations. One of the products of the program is a proposed revision of those portions of the DoD Ammunition and Explosives Safety Standards (6055.9-STD) dealing with underground magazines. After a thorough analysis of the results of the UAST and previous programs, a revised engineering relation has been proposed to establish the Inhabited Building Distance (IBD) for airblast hazards. The proposed equation for IBD is,

$$R = 161.0 \; D \left(\frac{W}{V_E} \right)^{\frac{1}{2.8}} \left(\frac{1}{p_{SO}} \right)^{\frac{1}{1.4}} \qquad \textbf{(1)}$$

where R: IBD distance from portal, along the extended tunnel axis (feet)

D: effective hydraulic diameter that controls dynamic flow issuing from the portal (feet). Note: Compute D, using the minimum cross-sectional area of the tunnel (A) that is located within five tunnel diameters of the opening, as D=4 A/p, where A is the area and p is the perimeter.

W: maximum credible event (MCE) (pounds)

V_E: volume engulfed by the blast wavefront within the tunnel system at the time the waveform arrives at the point of interest (ft^3)

p_{so}: airblast overpressure at the IBD, taken as 0.9 psi (6.2 kPa) in this analysis

RESULTS OF CALCULATION

The peak overpressures calculated with the BLASTX3.5 model were compared to measured values from the selected tests. Portal pressures were extrapolated from the measured and calculated values at stations just inside the tunnels (Table 3). In addition, comparisons are made for IBD (Table 3) obtained from three sources: 1) measured free-field pressure data, 2) BLASTX-calculated peak values, and 3) the calculated IBD using Equation 1. The comparisons are discussed in the following sections.

U.S. Intermediate-Scale Tests: Overpressures recorded at the Linchburg Mine test site are compared to those calculated with the "gas only" version of BLASTX in Figures 6, 7, 8, and 9. Test 1 was a detonation of a single cube of Comp B (engulfed loading density = 0.005 kg/m^3) in the main mine drift. The peak overpressure for this test are plotted versus the distance from the center of the charge in Figure 6. (The remaining data are plotted versus distance from the rear wall of the chamber.) As shown here, the BLASTX-calculated overpressures are much lower than the measured data (Test 1). As the loading density is increased, the BLASTX-calculated pressures increase at a greater rate than the measured values. The data from Test 3 (engulfed volume loading density = 0.144 kg/m^3) indicated that the measured peak overpressures are greater than the BLASTX-calculated values close to the charge, but attenuate faster with distance than the calculated data (Figure 7). As the blast wave passes through the Left Test Drift, the BLASTX data surpasses the measured data and continues to exceed it as the blast wave travels to the portal. As the loading density (engulfed volume loading density = 0.850 and 0.925, Tests 6 and 8, respectively) is increased to larger values, the cross-over point (from measured values > calculated to measured < calculated) recedes towards the detonation chamber and the over prediction by the BLASTX calculation becomes even greater.

A comparison of the measured and calculated (BLASTX and equation 1) peak free-field overpressure data are also presented in Figures 6, 7, 8, and 9. As the loading density is increased the difference between the measured and calculated data decreases. Note also that the calculated values (BLASTX and Equation 1) are in close agreement, but both are much greater than the measured data. Free-field instruments were not used for Test 8.

The ratio of the measured to BLASTX calculated peak pressure for selected U.S. Intermediate-Scale Tests is plotted versus distance in Figure 10. The data shows scatter but trends are apparent. The data from Test 1 exceeds the +50 percent error line. The data from Test 3 falls within the $\pm$ 50 percent error band until the engulfed loading density falls below 0.6 kg/m^3. Tests 6 and 8 show a similar trend but these data exceed the -50 percent error line at engulfed volume loading densities of 6.4 and 3.5, respectively.

ROK Intermediate-Scale Tests: Comparisons of measured and calculated (BLASTX and Equation 1) peak pressures from the ROK Intermediate-Scale Test Program are presented in Figure 11, 12, 13, 14, 15, 16 and 17. Measured and calculated data from the ROK Test 3 (Tunnel 1, Chamber 3, engulfed volume loading density = 2.97) are plotted in Figure 11. As shown here BLASTX over predicts the pressures near the portal and in the free-field outside the portal. In this example Equation 1 provides a much better prediction of IBD than the BLASTX model although both methods produce safety conservative results.

Figure 12 presents a comparison of the results from the ROK Test 7 (Tunnel 3, Chamber 1, engulfed volume loading density = 1.04) with the BLASTX computation. The agreement between the internal measured peak data and BLASTX computed values is excellent. Outside the portal, in the free-field, BLASTX over predicts IBD by a factor of 2, slightly greater than the distance predicted by Equation 1.

Results from the ROK Test 8 (Tunnel 4, Chamber 1, engulfed volume loading density = 3.080 kg/m^3) is presented in Figure 13. In this comparison, agreement is very good both internally and in the free-field. The measured data does not extend to the IBD but closely matches the related BLASTX computed values in the free-field. The BLASTX model predicts slightly greater IBD than obtained from Equation 1.

The ROK Test 12 was conducted in the Tunnel 5 complex with two exits. The detonation chamber was located at approximately the center of the tunnel arc, nearly equi-distance from both exits. A comparison between the measured peak data and the BLASTX-computed values for the right exit is shown in Figure 14 engulfed volume loading density = 1.13 kg/m^3). A barricade was placed outside the right exit. The revised standards (DoD 6055.9-STD) allow a distance to the IBD of 0.5 times the unbarricaded distance. Thus the free-field distances shown are the unbarricaded distances calculated by BLASTX and Equation 1 divided by 2. As is shown in Figure 14 the reduced distances are only slightly greater that the measured IBD. Similarly, a comparison for the left (unbarricaded) portal (Figure 15, engulfed volume loading density = 1.09 kg/m^3) indicates similar good agreement, although the measured free-field data does not extend to the IBD.

After the first test at the ROK Tunnel 4 (Test 8), additional excavation was done to create a new detonation chamber, an expansion chamber, and a second exit (Figure 6). ROK Test 14 was conducted in this modified Tunnel 4 complex. A comparison of the measured data and calculated BLASTX values for the right portal (engulfed volume loading density = 0.30 kg/m^3) are shown in Figure 16. The BLASTX calculations show good agreement with the data. Beyond the portal, BLASTX slightly over-predicts the measured IBD. There is very good agreement between the measured and that predicted by Equation 1. The results for the left exit (Figure 17, engulfed volume loading density = 0.39 kg/m^3) shows similar agreement.

The ratio of measured to calculated (BLASTX) pressure for the ROK Intermediate-Scale Test Program are plotted versus distance in Figure 18. As shown here, the majority of the ROK data fall between the $\pm$ 50 percent error bands. The notable exceptions are the Test 3 free-field data and the Test 7 from just inside the portal through the free-field which exceed the $\pm$ 50 percent data limits. The data from Test 7 exhibit considerable scatter in this region with a few data point near the portal in good agreement with the BLASTX calculated values.

Älvdalen KLOTZ Club Tests: Comparisons of measured and calculated (BLASTX and Equation 1) peak pressures from three KLOTZ Club Underground Magazine Tests at Älvdalen, Sweden, are presented in Figures 19, 20, and 21. A comparison of measured peak pressures and the BLASTX computed values for Test 7 (engulfed volume loading density = 1.101 kg/m^3) is shown in Figure 19. Although the measurements were limited, good agreement is shown between the measured and calculated peak values. A second test (Test 8) was performed in Chamber A with an increased quantity of explosives (5,000 kg of ANFO). These data (measured and calculated) are presented in Figure 20 (engulfed volume loading density = 5.506 kg/m^3). Here again, the measured data are limited, a few data points inside the tunnel and one data in the free-field outside the portal. However, the limited measured peak values show reasonable agreement with the computed BLASTX data. Similar agreement is shown for the very limited peak measurements from Test 9 (Figure 21), a 5,000 kg ANFO detonation in Chamber B (engulfed volume loading density = 5.506 kg/m^3). The axis of this chamber was at 45^o to the main drift with a debris trap in line with the chamber access drift.

The ratio of measured to calculated (BLASTX) pressure for the KLOTZ Club Älvdalen Tests 7, 8, and 9 are plotted versus distance in Figure 22. As shown here Tests 8 and 9 internal data are contained within the $\pm$ 50 percent error band. All of the Test 7 and the free-field data beyond Test 8 fall outside $\pm$50 percent error band. Free-field data were not obtained from Test 9.

Camp Stanley 1/3-Scale Validation Tests: The 1/3-Scale Validation Test was preceded by two smaller calibration experiments to attempt to evaluate scaling of explosives detonations in underground magazines. The data from Test 1 (10.7 kg) detonated in the donor bay (B) is presented in Figure 23 (engulfed volume loading density = 0.023 kg/m^3). The BLASTX calculation under predicts the peak pressures, both internal and free-field. A similar result was observed from the U.S. Intermediate-Scale, Test 1 where a comparable quantity of explosives were detonated in the main Linchburg Mine drift. Data from a second calibration test (57.9 kg) is presented in Figure 24 (engulfed volume loading density = 0.134 kg/m^3). As seen here, the calculated internal pressures (BLASTX) are less than the measured data. However, in the free-field, the measured and calculated (BLASTX and Equation 1) values are in good agreement. The results of the Validation Test (336 kg detonation) are presented in Figure 25 (engulfed volume loading density = 0.707 kg/m^3). Good agreement is shown between measured and calculated data from Test 3 (within the scatter of the measured peak data).

The ratio of the measured to BLASTX calculated peak pressure for the 1/3-Scale Camp Stanley Validation Test is plotted versus distance in Figure 26. The results from Test 1 tend to plot at or above the +50 percent error limit. The remainder of the Validation Test data fall between the $\pm$ 50 percent error limits.

CONCLUSIONS

The comparisons presented herein show that the BLASTX computer models yield safety conservative predictions of Inhabited Building Distance except for very low loading densities (engulfed volume loading densities less than 0.03 kg/m^3). The BLASTX predictions for experiments with engulfed volume loading densities greater than 0.03 kg/m^3 were more safety conservative than the IBD relation (Equation 1).

The degree of over or under prediction by BLASTX is presented in plots of the prediction ratio (measured divided by calculated pressure) versus distance from the source. While these graphs show considerable scatter, trends are observed. The prediction ration from the ROK, KLOTZ Club and Camp Stanley tests (internal data) fall within the $\pm$50 percent error band (from 0.5 to 2 times the measured value) when the engulfed volume loading density is greater than 0.03 kg/m^3. A notable exception to this is the KLOTZ Club Test 7 with a 1,000 kg ANFO detonation. As shown in Figure 22 these data exceed the +50 percent error limit (the data are more than 2 times larger than the BLASTX calculated values). The different behavior observed from the KLOTZ Club tests may be due to the explosive source (ANFO). The mass of ANFO has not been converted to NEQ in this analysis.

The engulfed volume loading density of Test 1 of the U.S. Intermediate-Scale UAST Program was 0.005 and prediction ratio for this data plot as expected, above the +50 percent error line. The data prediction ratio from subsequent UAST detonations plot for the most part within the $\pm$50 percent error band until the engulfed volume loading density falls below some value which varies with the chamber loading density. The cross over point occurs at a engulfed loading density of 0.6 kg/m^3 (Test 3, NEQ = 378.0 kg), 6.4 kg/m^3 (Test 6, NEQ = 2826.4 kg) and 3.5 kg/m^3 (Test 8, NEQ = 3076.8 kg). Thus, it would appear that BLASTX produces acceptable predictions (< $\pm$ 50 percent error) when the engulfed volume loading density falls between 0.03 and 3.5 kg/m^3

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Table 1. Description of the experiments calculated with BLASTX for this comparison.

TEST NO.	LOADING DENSITY (kg/m^3) CHAMBER VOLUME	LOADING DENSITY (kg/m^3) SHOCK ENGULFED VOLUME	NET EXPLOSIVE QUANTITY (kg)	CHARGE LOCATION
US/ROK UAST PROGRAM -- U.S. INTERMEDIATE-SCALE TESTS[1]:				
1	-----	0.005	16.7	Main Adit
3	5.5	0.114	378.0	Chamber 4
6	37.3	0.850	2826.4	Chamber 4
8	46.5	0.925	3076.5	Chamber 2, w/ Expansion Chamber
US/ROK UAST PROGRAM -- ROK INTERMEDIATE-SCALE TESTS[2]:				
3	26.7	2.968	244.0	Chamber 3, Tunnel 1
7	9.1	0.980	244.0	Chamber 1, Tunnel 3
8	25.6	3.080	223.0	Chamber 1, Tunnel 4
12	21.4	1.130	375.0	Chamber 2, Tunnel 5
14	10.6	0.390 (L)[3] 0.338 (R)	75.0	Chamber 2, Tunnel 4
ÄLVDALEN KLOTZ CLUB TESTS[4]:				
7	2.9	1.101	1000.0	Chamber A
8	14.7	5.506	5000.0	Chamber A
9	22.5	5.506	5000.0	Chamber B

[1] Comp B Explosive Charges

[2] C-4 Explosive Charges

[3] (L) and (R) indicate Left and Right Exit

[4] ANFO Explosive Charge

Table 1. Description of the experiments calculated with BLASTX for this comparison (concluded).

TEST NO.	LOADING DENSITY (kg/m^3)		NET EXPLOSIVE QUANTITY (kg)	CHARGE LOCATION
	CHAMBER VOLUME	ENGULFED VOLUME		
CAMP STANLEY VALIDATION TESTS[5]				
1	0.4	0.023	10.7	Center Bay
2	2.1	0.134	57.9	Center Bay
3	12.0	0.707	336.0	Center Bay

[5] Reclaimed Comp B

Table 2. Calculated (BLASTX and DoD 6055.9-STD) and measured portal pressure and Inhabited Building Distances for selected large-scale underground magazine tests.

TEST No.	NEQ	PORTAL PRESSURE[6] (kPa)		INHABITED BUILDING DISTANCE (m)		
		MEASURED	BLASTX	MEASURED	BLASTX	DDESB 6055.9-STD
US/ROK UAST PROGRAM -- U.S. INTERMEDIATE-SCALE TESTS:						
1	16.7	12.8	2.0	2.1	-----	17.2
3	378.0	5.2	93.3	----	37.8	55.0
6	2826.4	85.9	440.4	24.9	113.4	112.8
8	3076.5	0.2	441.7	-----	112.9	116.2
US/ROK UAST PROGRAM -- ROK INTERMEDIATE-SCALE TESTS:						
3	244.0	1332.0	2471.0	86.1	176.1	119.9
7	244.0	413.0	624.5	56.3	174.4	87.1
8	223.0	1967.0	1570.9	-----	160.9	131.1
12[7]	375.0	498.7 (R) 866.9 (L)	1118.0 (R) 1165.0 (L)	31.3 (R) 77.5 (L)	39.5 (R) 135.9 (R)	38.5 (R) 126.0 (L)
14	75.0	966.9 (R) 136.2 (L)	624.3 (R) 353.2 (L)	55.9 (R) 58.9 (L)	83.2 (R) 82.8 (L)	59.6 (R) 56.3 (L)
ÄLVDALEN KLOTZ CLUB TESTS:						
7	1000.0	363.7	504.2	123.2	115.8	129.7
8	5000.0	2814.0	2158.0	165.4	345.8	230.5
9	5000.0	1712.0	2212.0	-----	256.4	230.5
CAMP STANLEY VALIDATION TESTS:						
1	10.7	85.5	34.2	25.5	12.6	23.8
2	57.9	301.7	205.7	67.7	50.6	43.5
3	336.0	1006.0	795.4	202.7	158.9	81.4

[6] (R) and (L) indicate right and left portals

[7] (R) portal w/ barricade, (L) portal w/o barricade

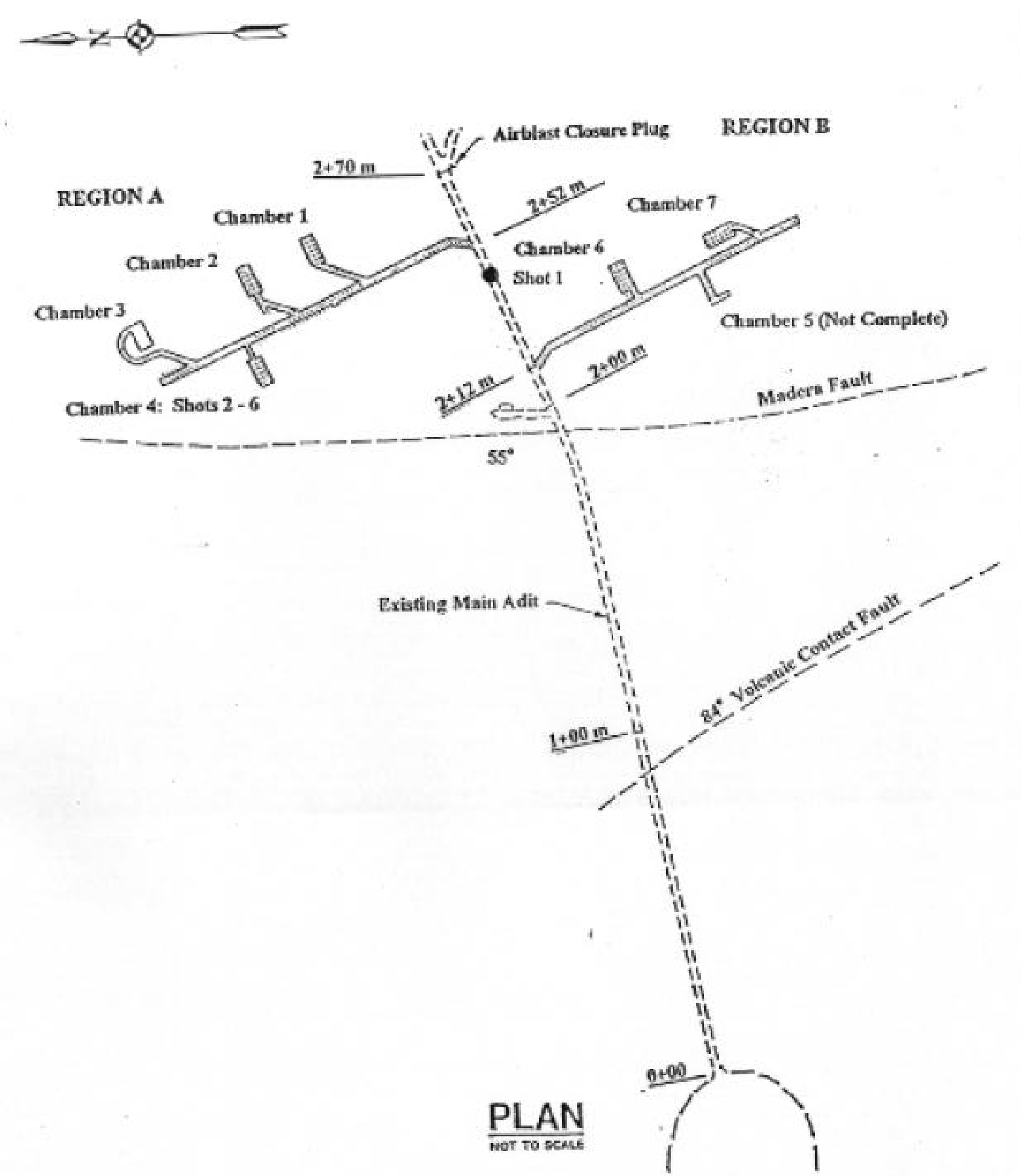


Figure 1. U.S./ROK UAST PROGRAM -- U.S. Intermediate-Scale test site layout, Tests 1 through 6 at the Linchburg Mine near Magdalena, NM.

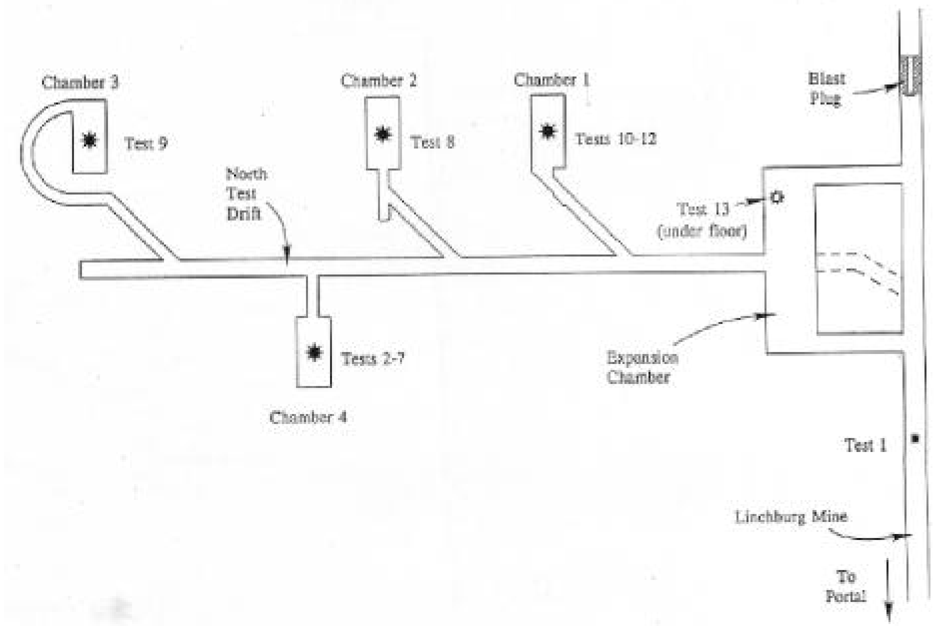


Figure 2. U.S./ROK UAST PROGRAM -- U.S. Intermediate-Scale test site layout at the Linchburg Mine near Magdalena, NM. Note: Tests 7 through 13 were conducted after excavation of the expansion chamber.

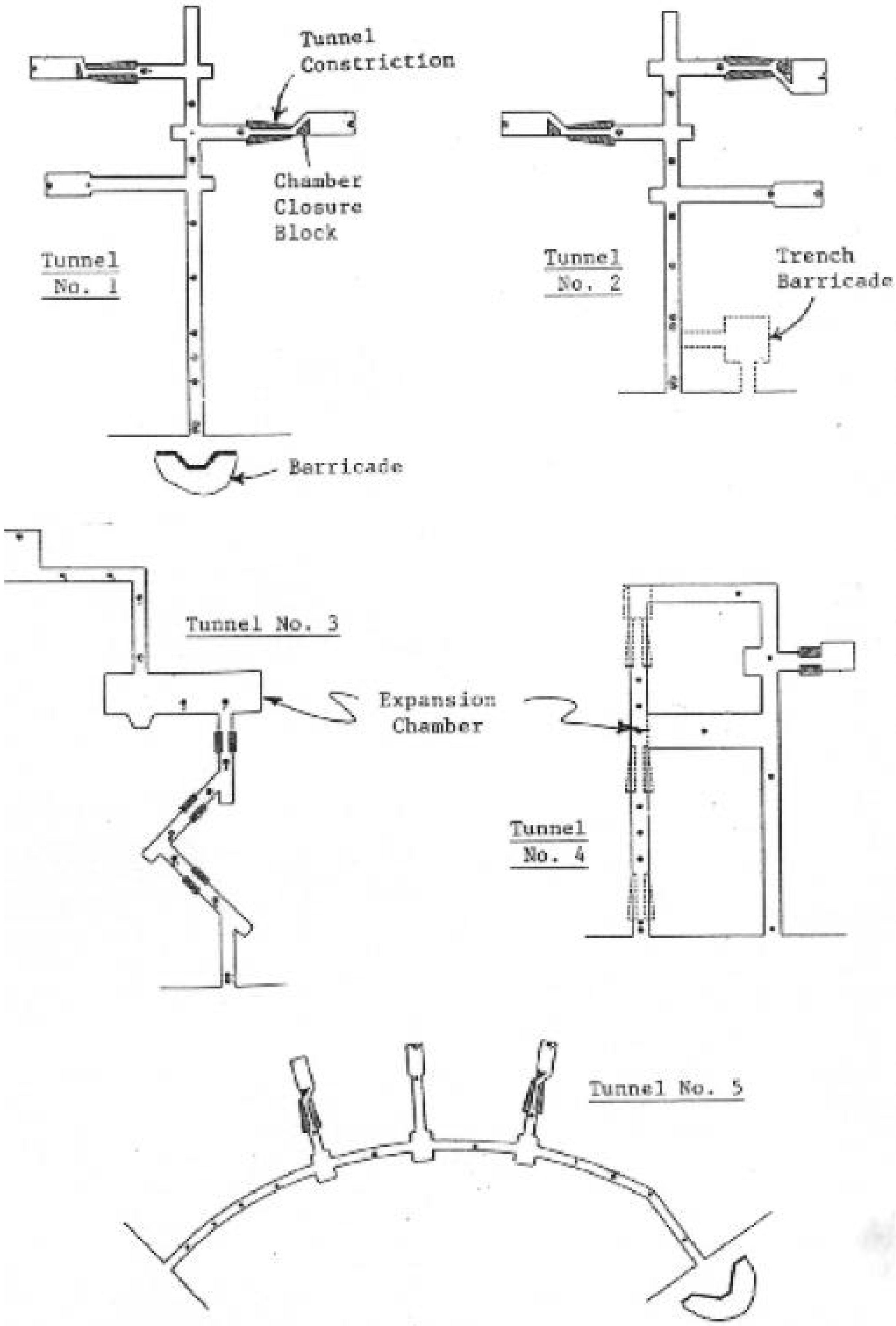


Figure 3. U.S./ROK UAST PROGRAM -- Tunnel geometries tested in ROK Intermediate-Scale tests.

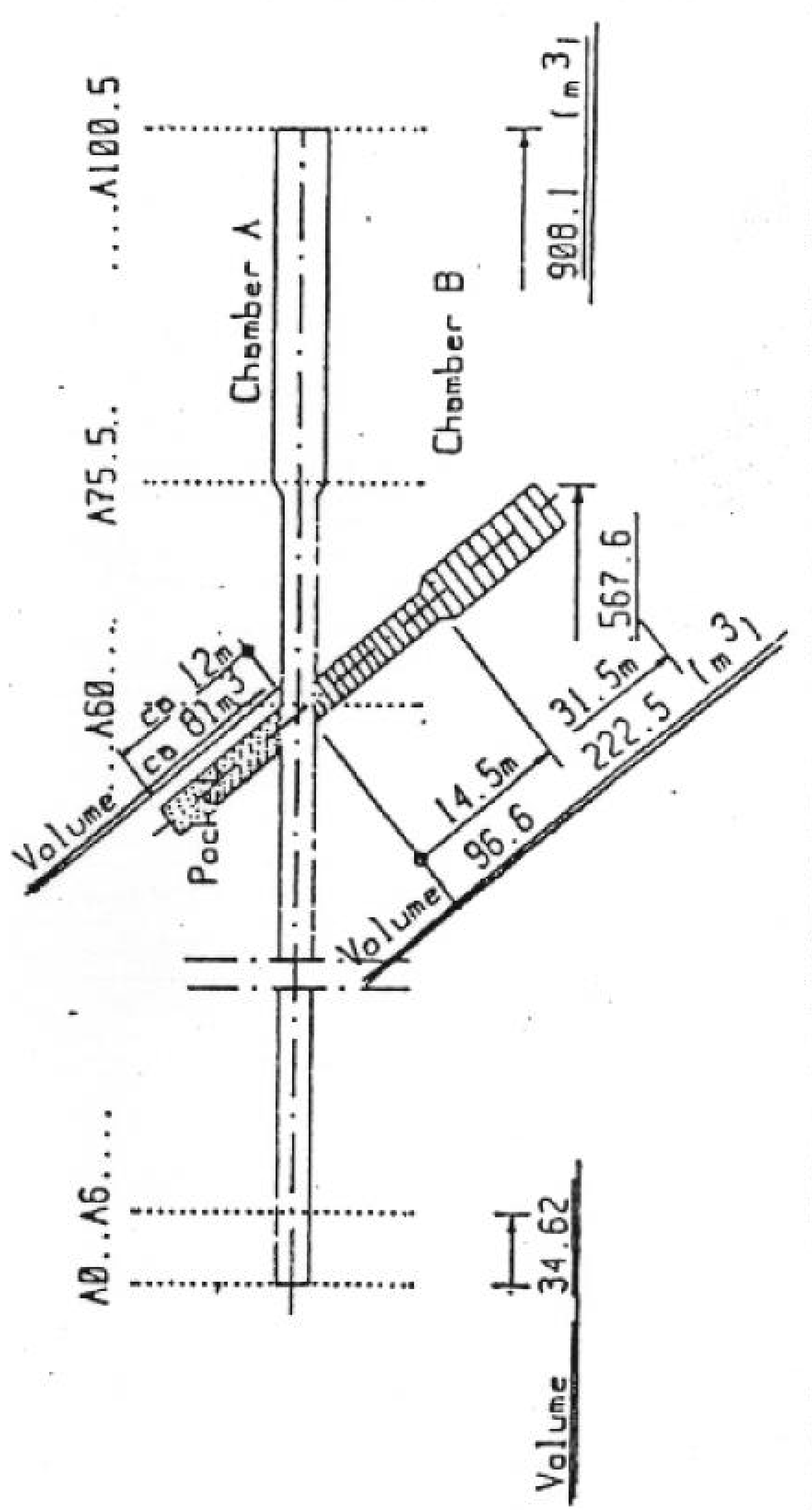


Figure 4. Test site layout for KLOTZ Club Tests 7, 8, 9, Älvdalen, Sweden.

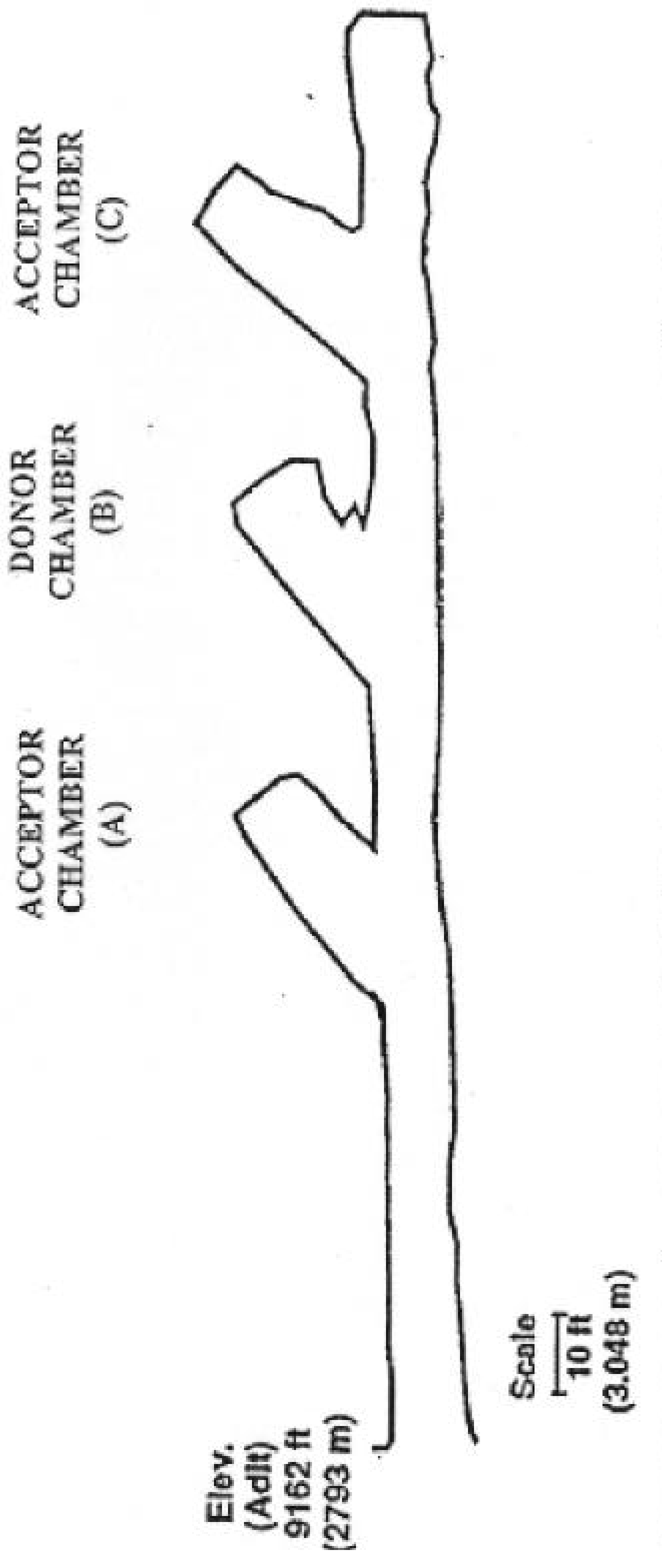


Figure 5. Test site layout for Camp Stanley Validation Tests 1, 2, and 3, Idaho Springs, Co.

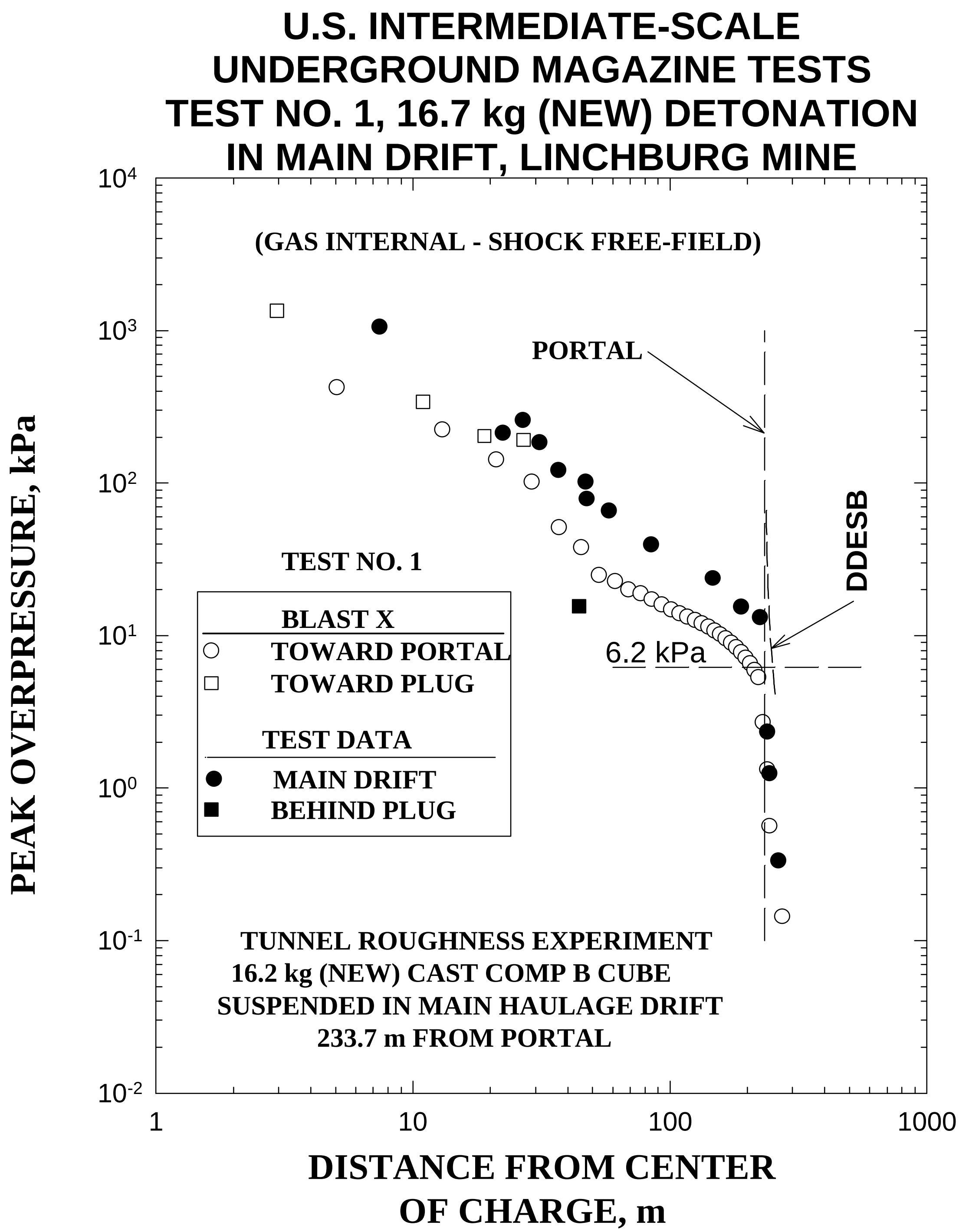


Figure 6. Peak overpressure versus distance from the center of the charge, U.S. Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 1 in the Linchburg Mine.

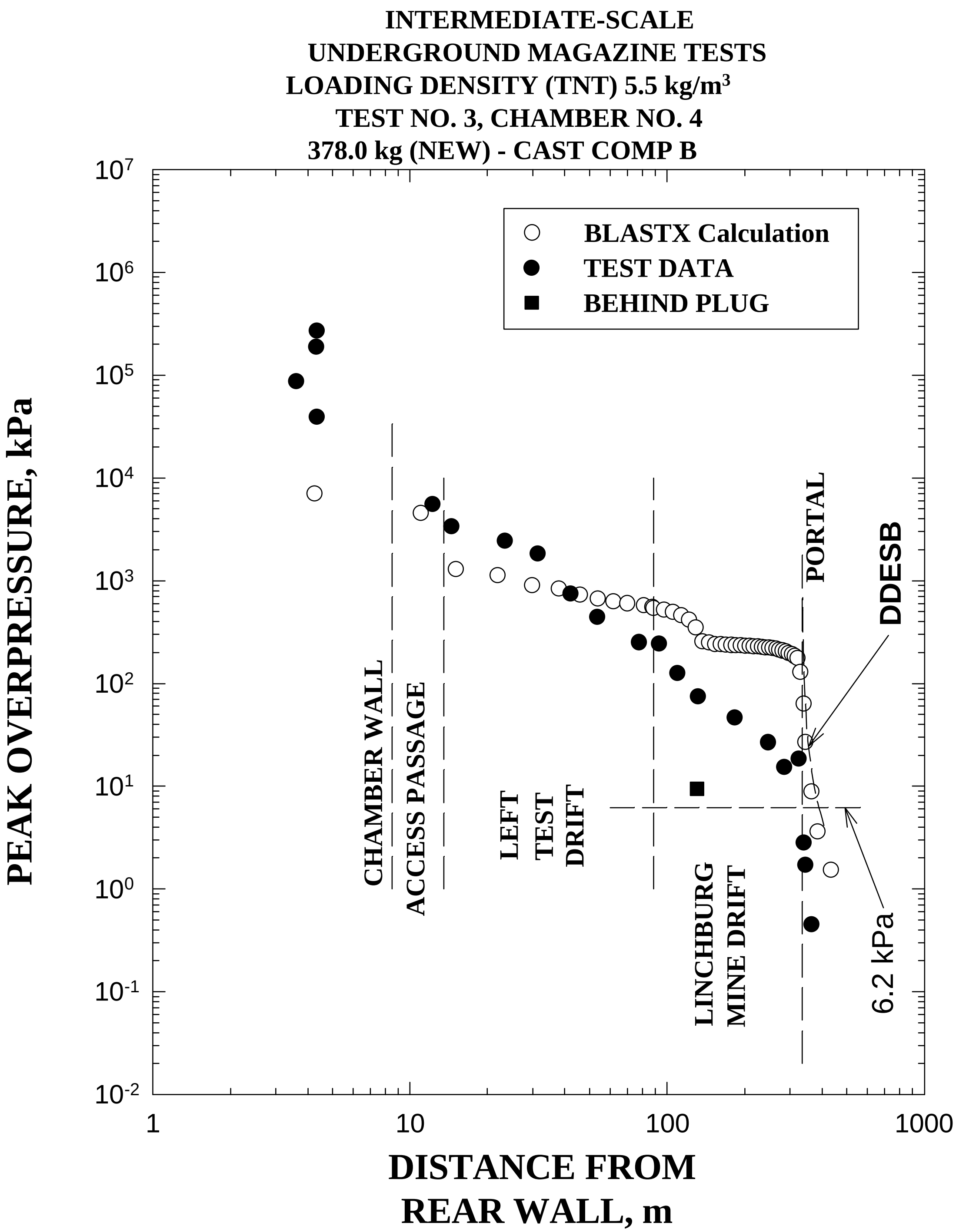


Figure 7. Peak overpressure versus distance from rear wall of Chamber 4, U.S. Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 3, Chamber 4 in the Linchburg Mine.

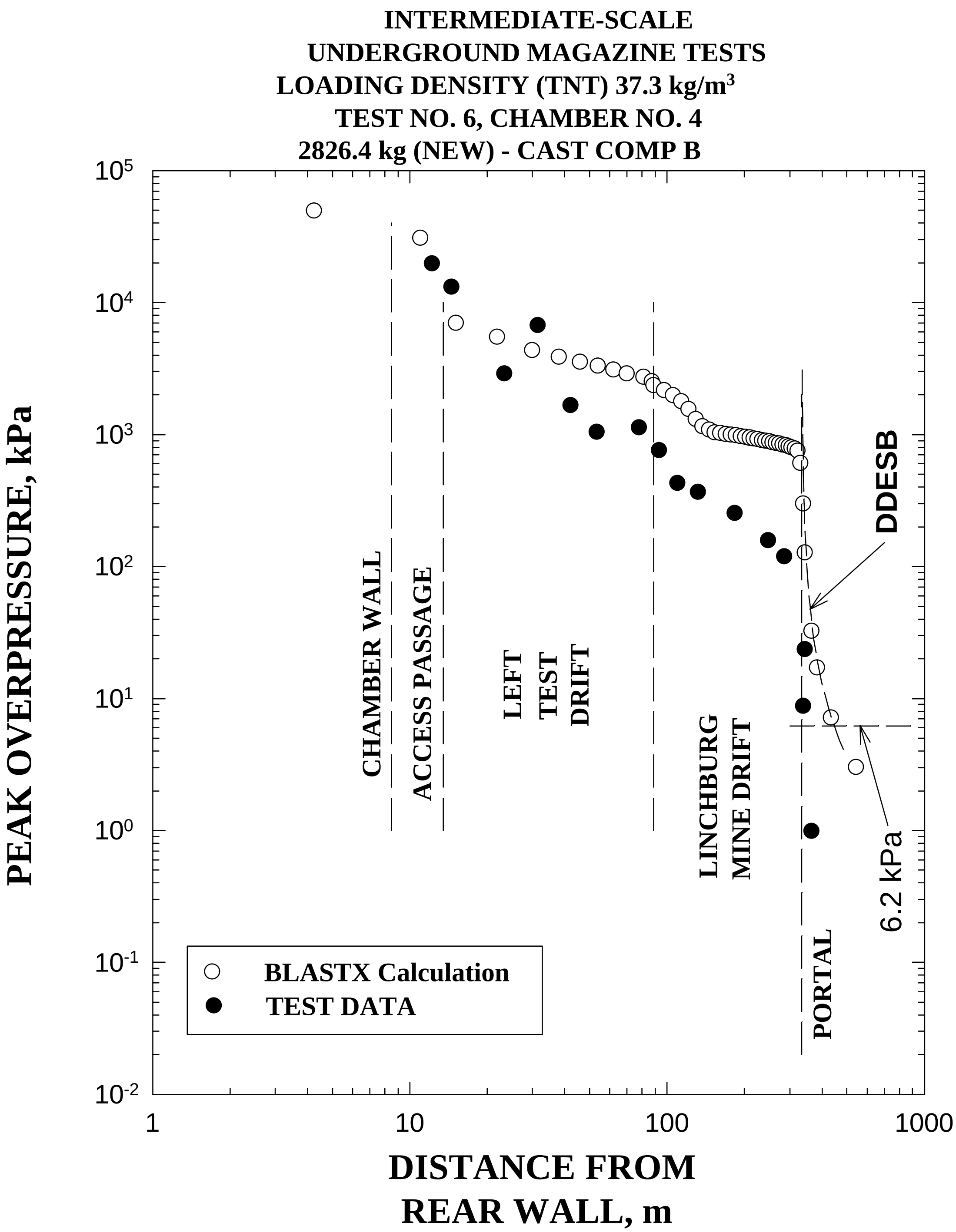


Figure 8. Peak overpressure versus distance from rear wall of Chamber 4, U.S. Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 6, Chamber 4 in the Linchburg Mine.

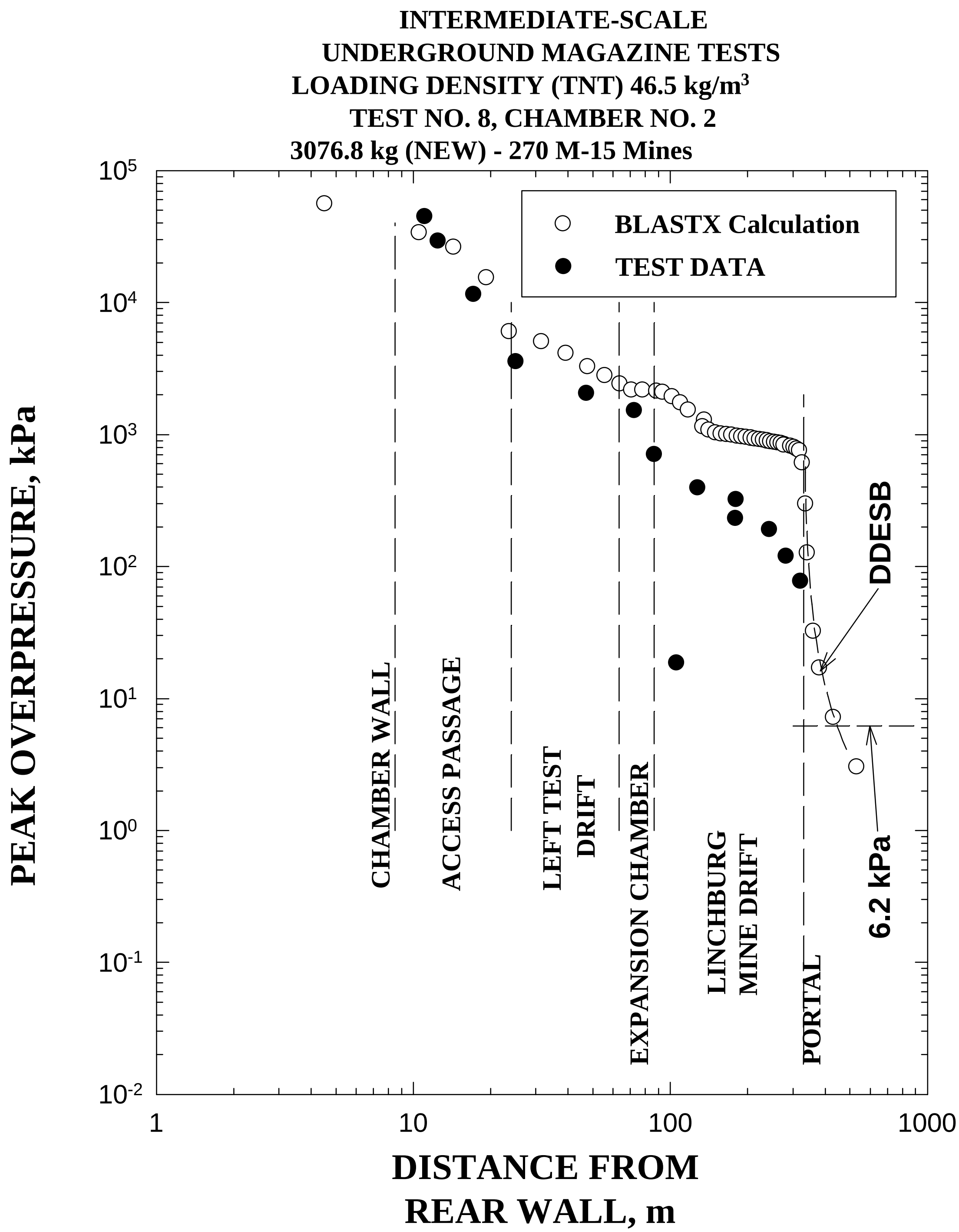


Figure 9. Peak overpressure versus distance from rear wall of Chamber 2, U.S. Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 8, Chamber 2 in the Linchburg Mine.

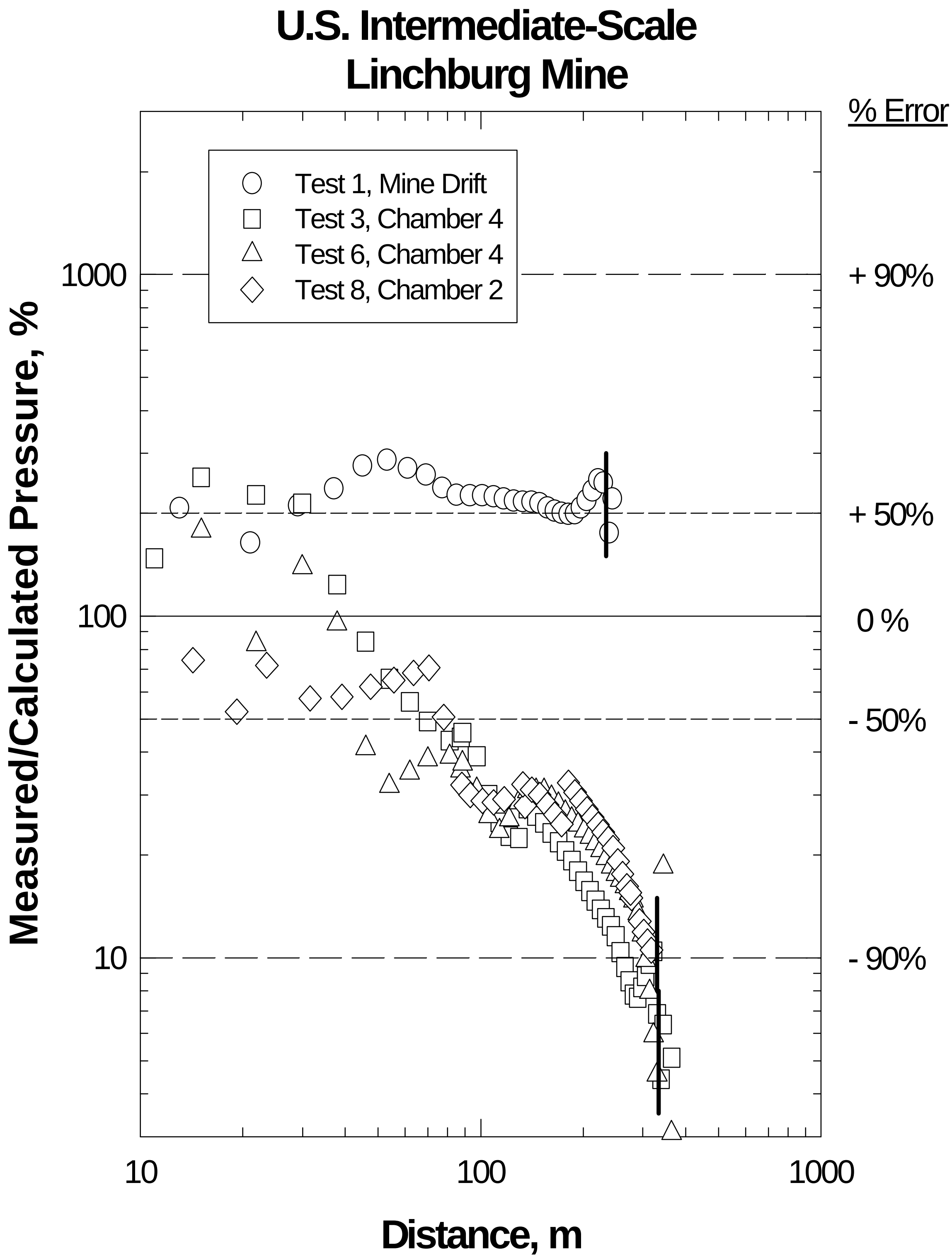


Figure 10. Prediction ratio (measured pressure divided by calculated (BLASTX) value) versus distance for the U.S. Intermediate-Scale UAST Program (Test 1, 3, 6, and 8).

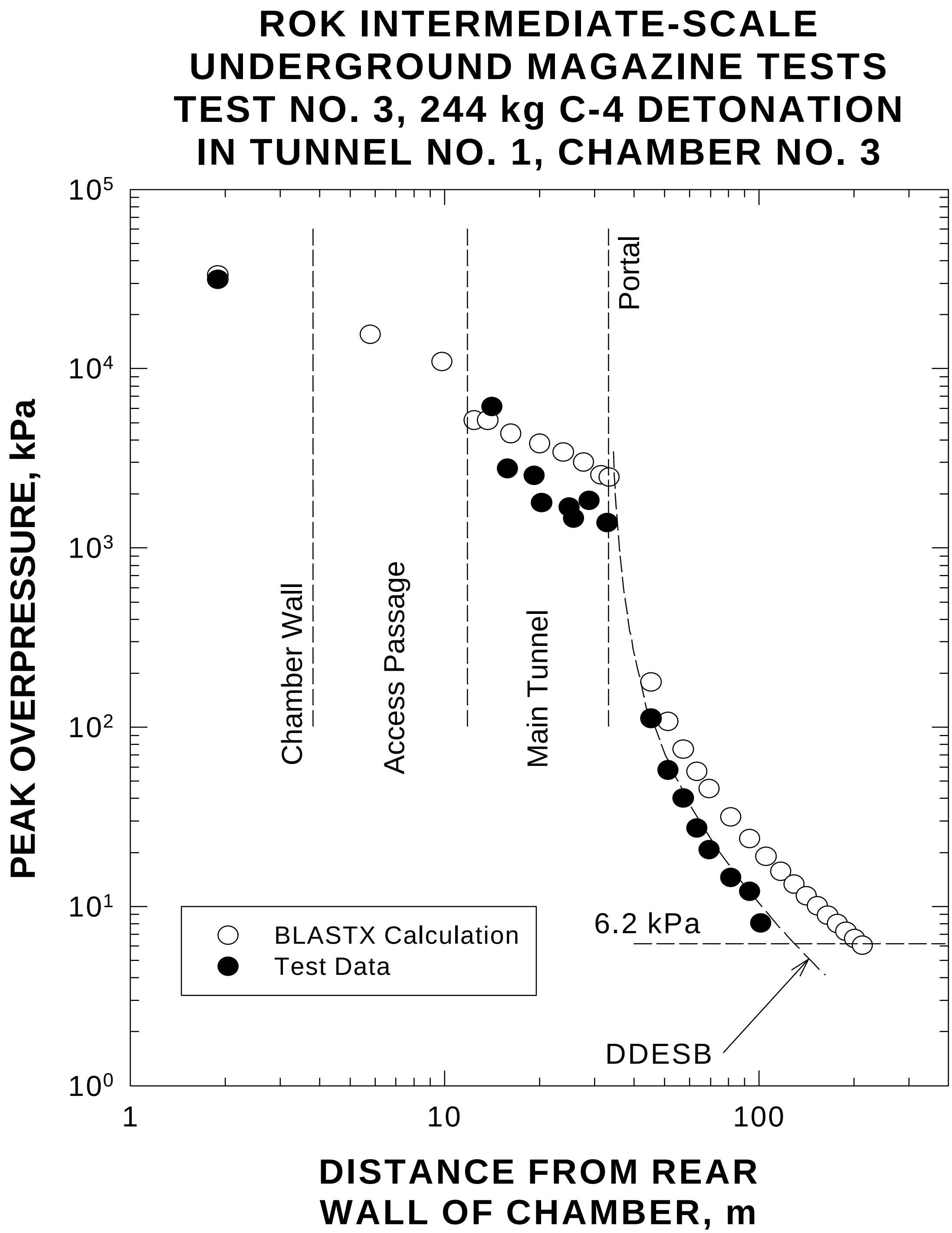
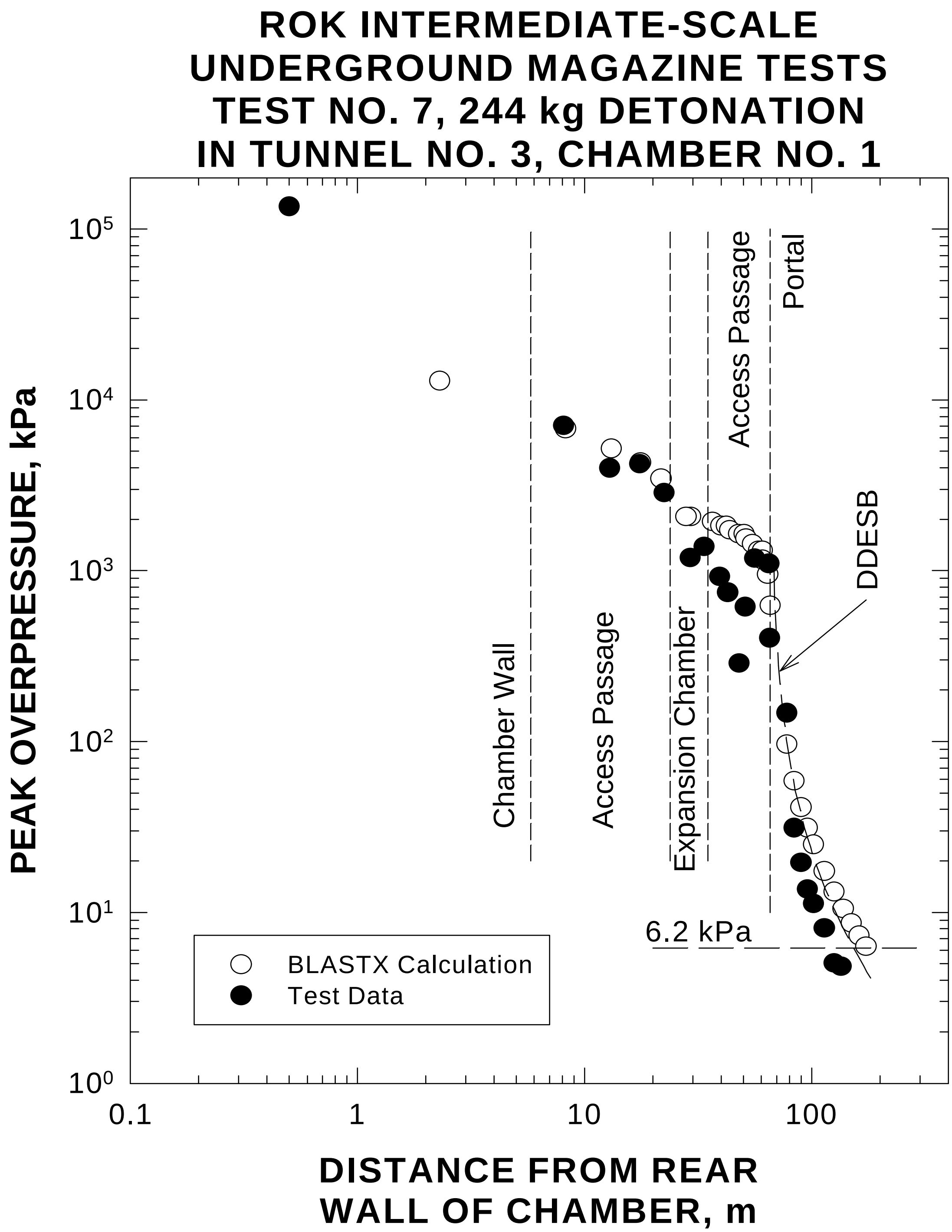


Figure 11. Peak overpressure versus distance from rear wall of Chamber 3, Tunnel 1, ROK Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 3 (no closure plug).



Fiigure 12. Peak overpressure versus distance from rear wall of Chamber 1, Tunnel 3, ROK Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 7 (with expansion chamber).

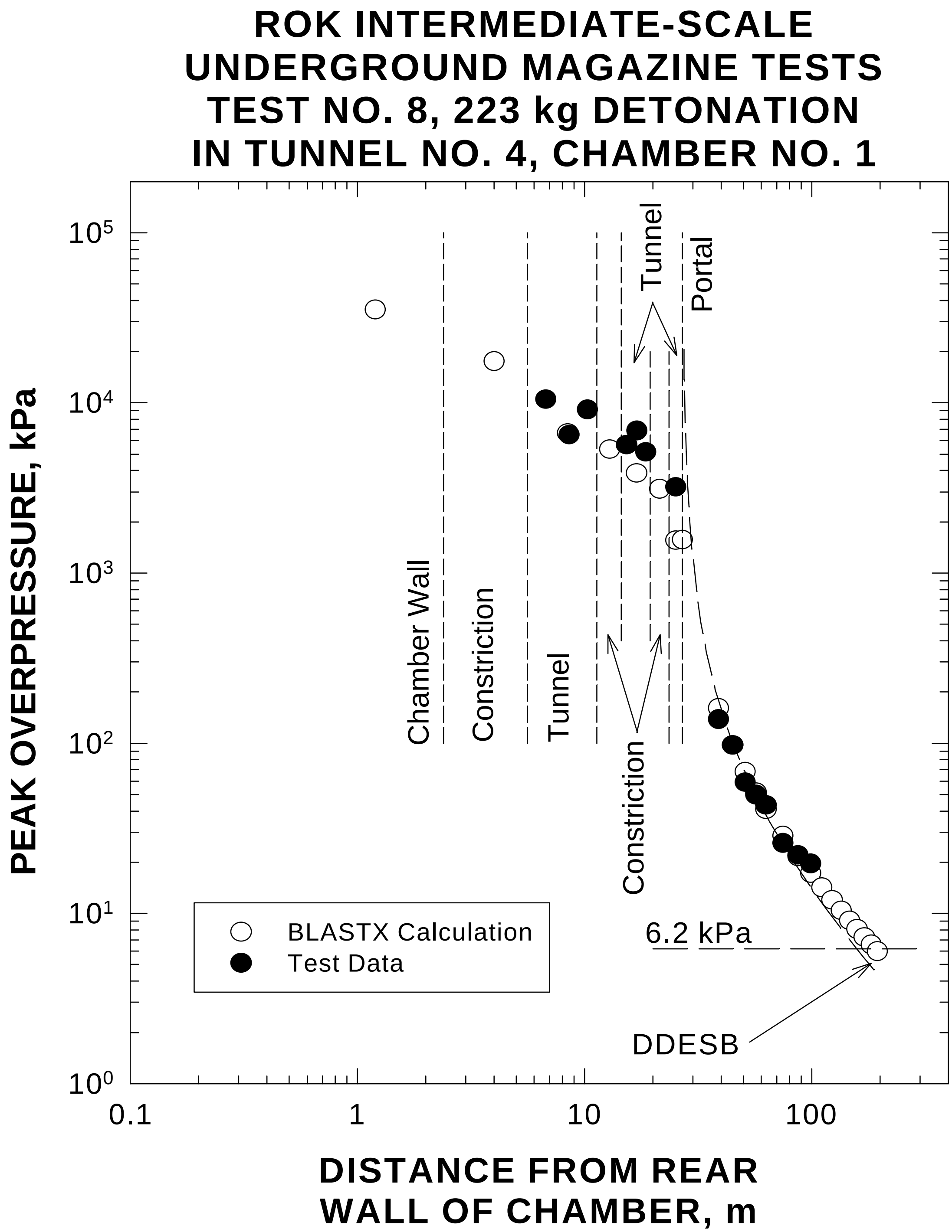


Figure 13. Peak overpressure versus distance from rear wall of Chamber 1, Tunnel 4, ROK Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 8 (with constrictions).

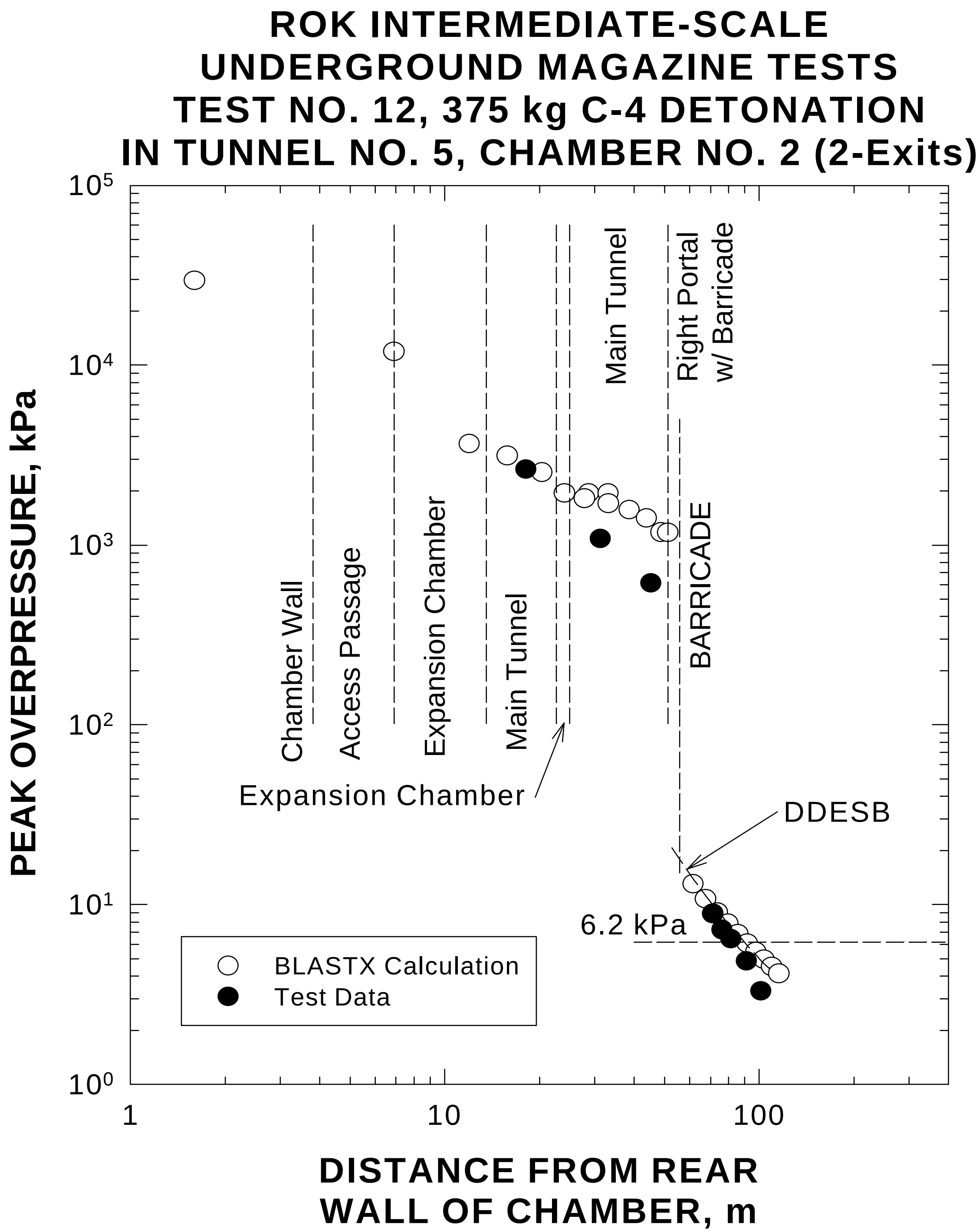


Figure 14. Peak overpressure versus distance from rear wall of Chamber 2, Tunnel 5, ROK Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 12 (right exit with barricade).

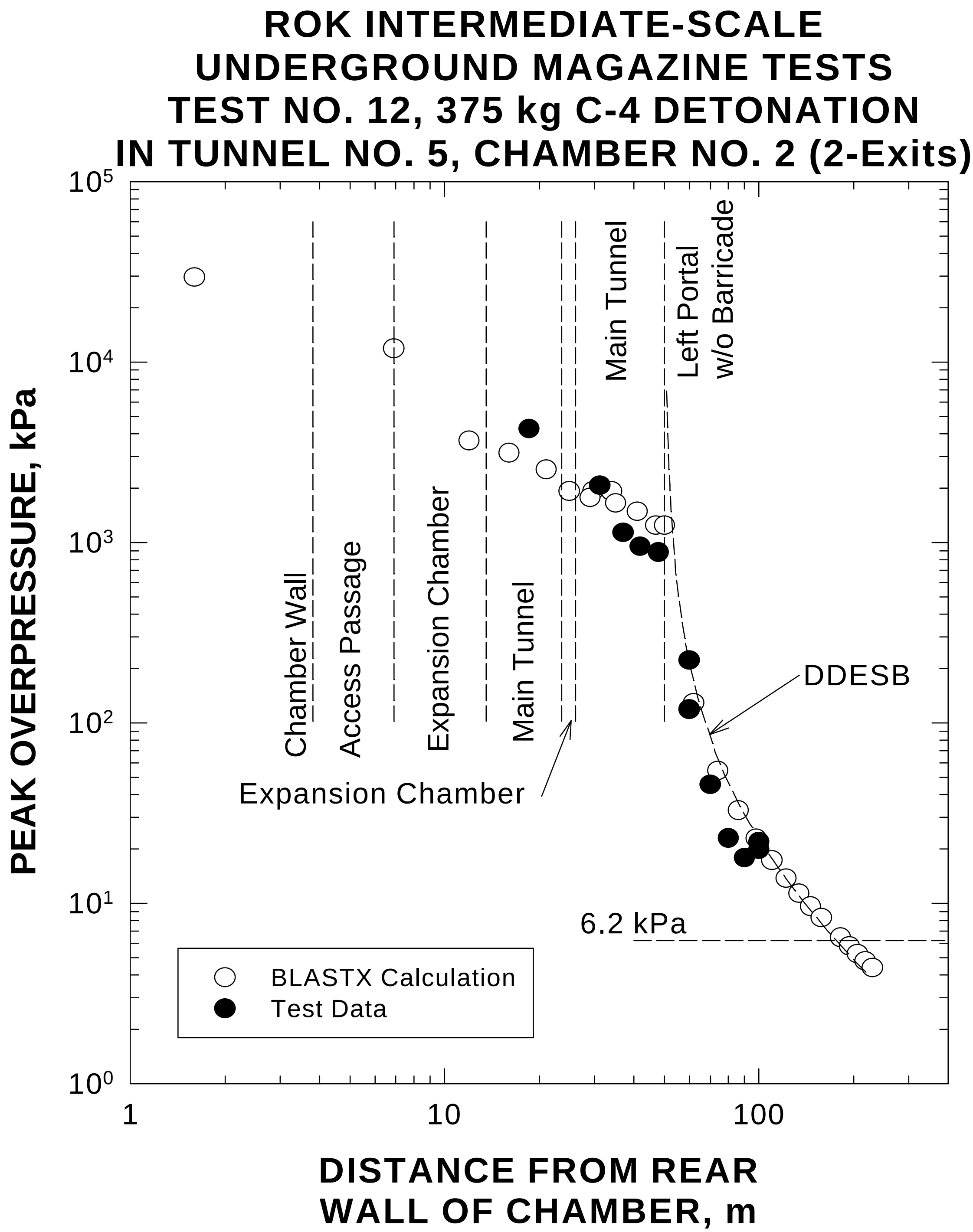


Figure 15. Peak overpressure versus distance from rear wall of Chamber 2, Tunnel 5, ROK Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 12 (left exit without barricade).

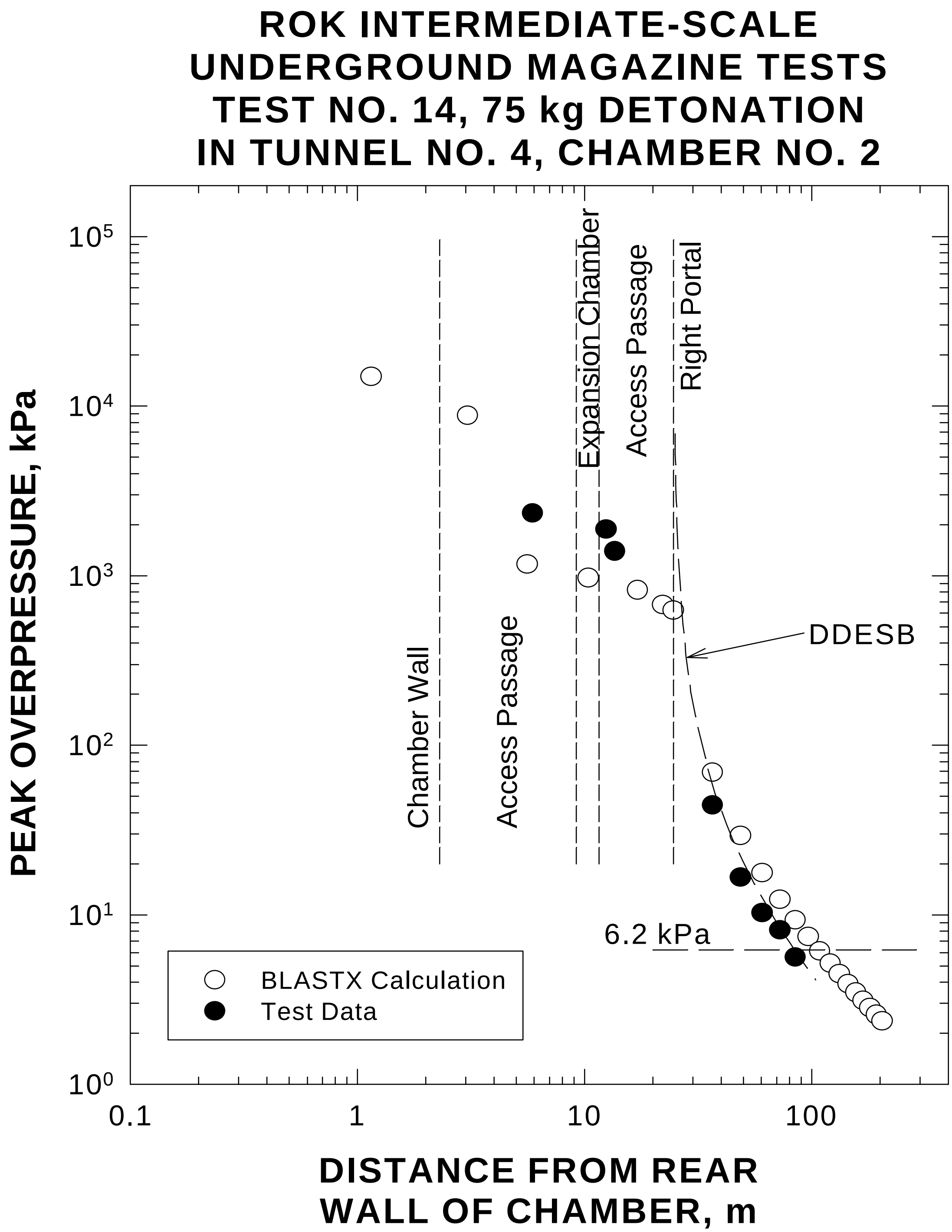


Figure 16. Peak overpressure versus distance from rear wall of Chamber 2, Tunnel 4, ROK Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Tests 14 (right exit).

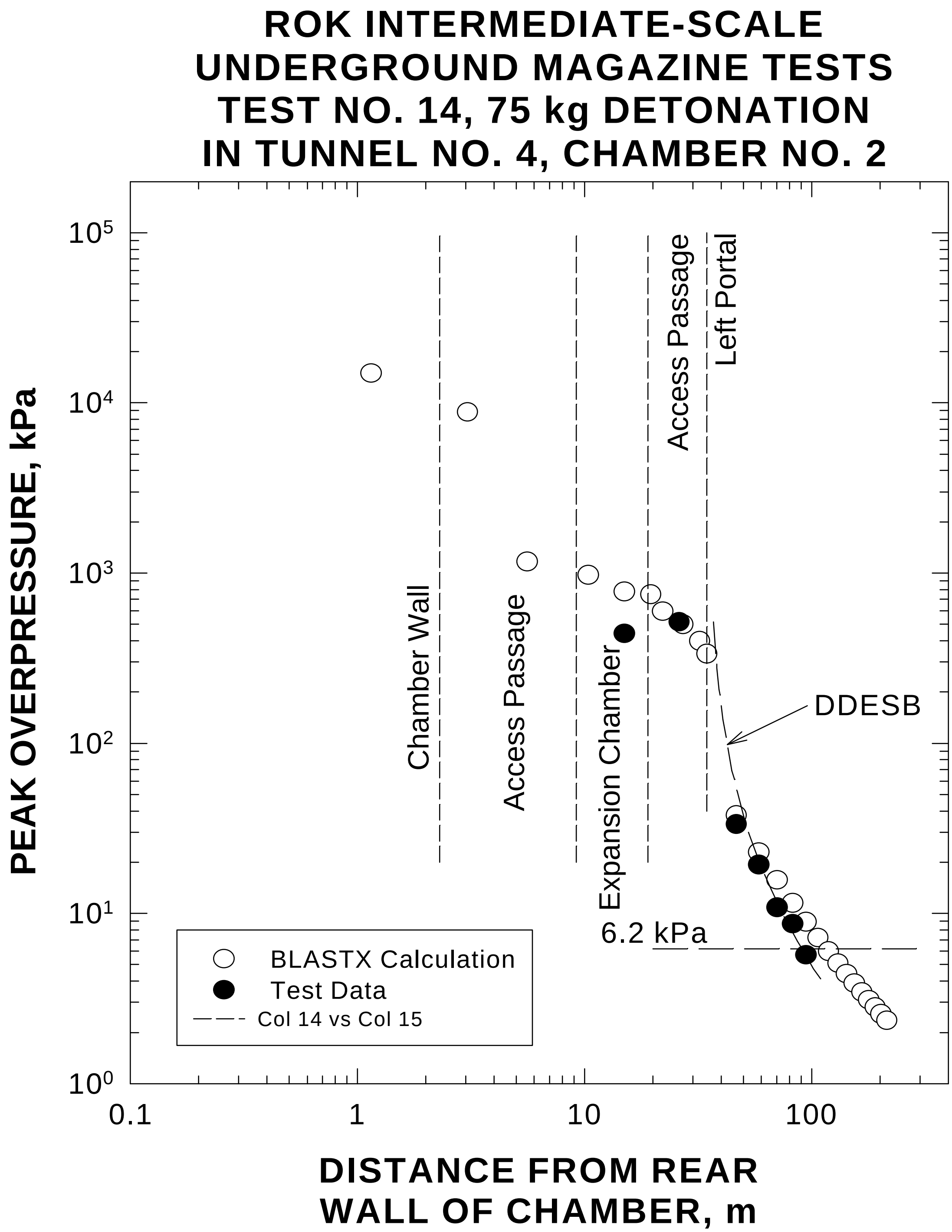


Figure 17. Peak overpressure versus distance from rear wall of Chamber 2, Tunnel 4, ROK Intermediate-Scale Test Program. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Test 14 (left exit).

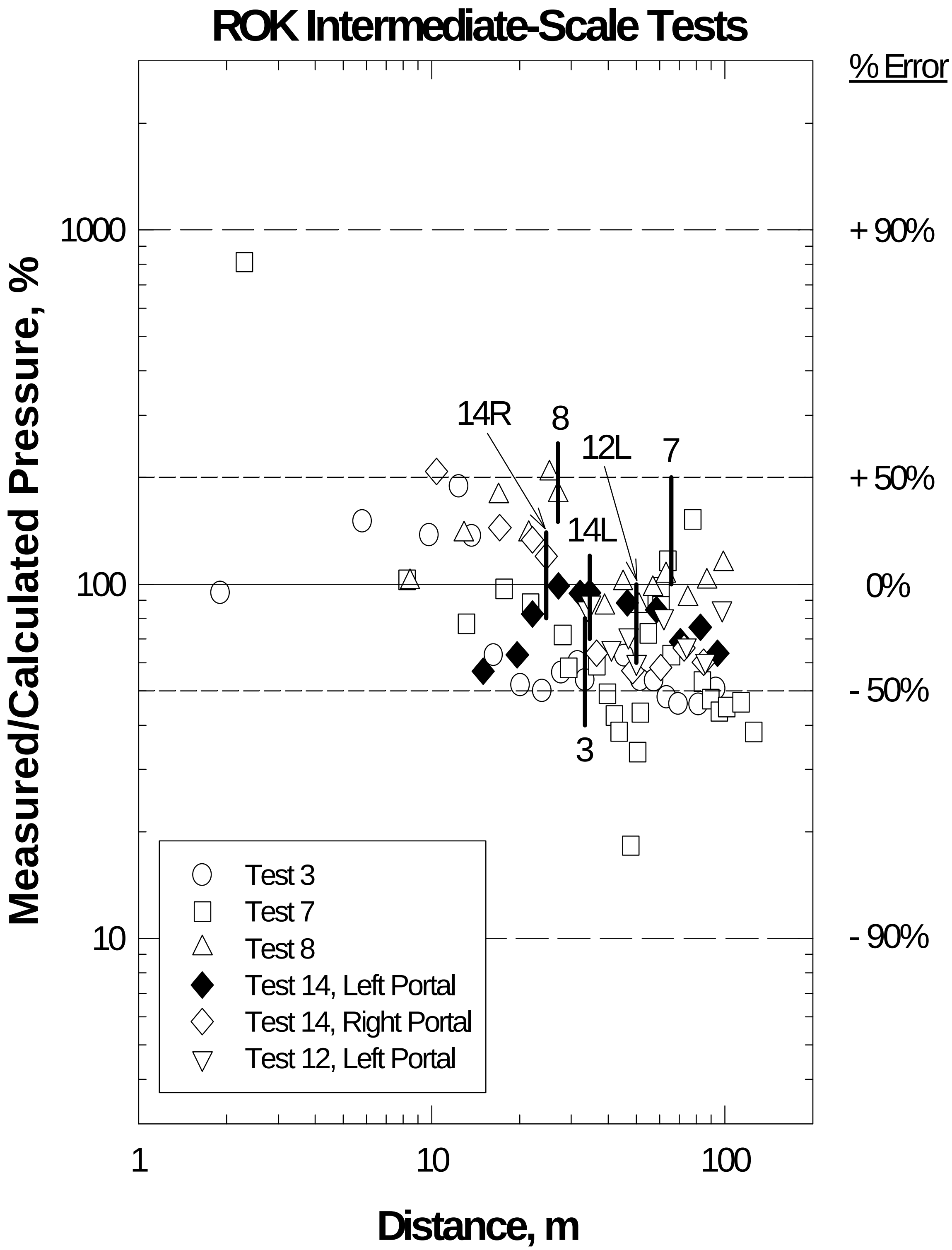


Figure 18. Prediction ratio (measured pressure divided by calculated (BLASTX) value) versus distance for the ROK Intermediate-Scale UAST Program (Tests 3, 7, 8, 12, and 14).

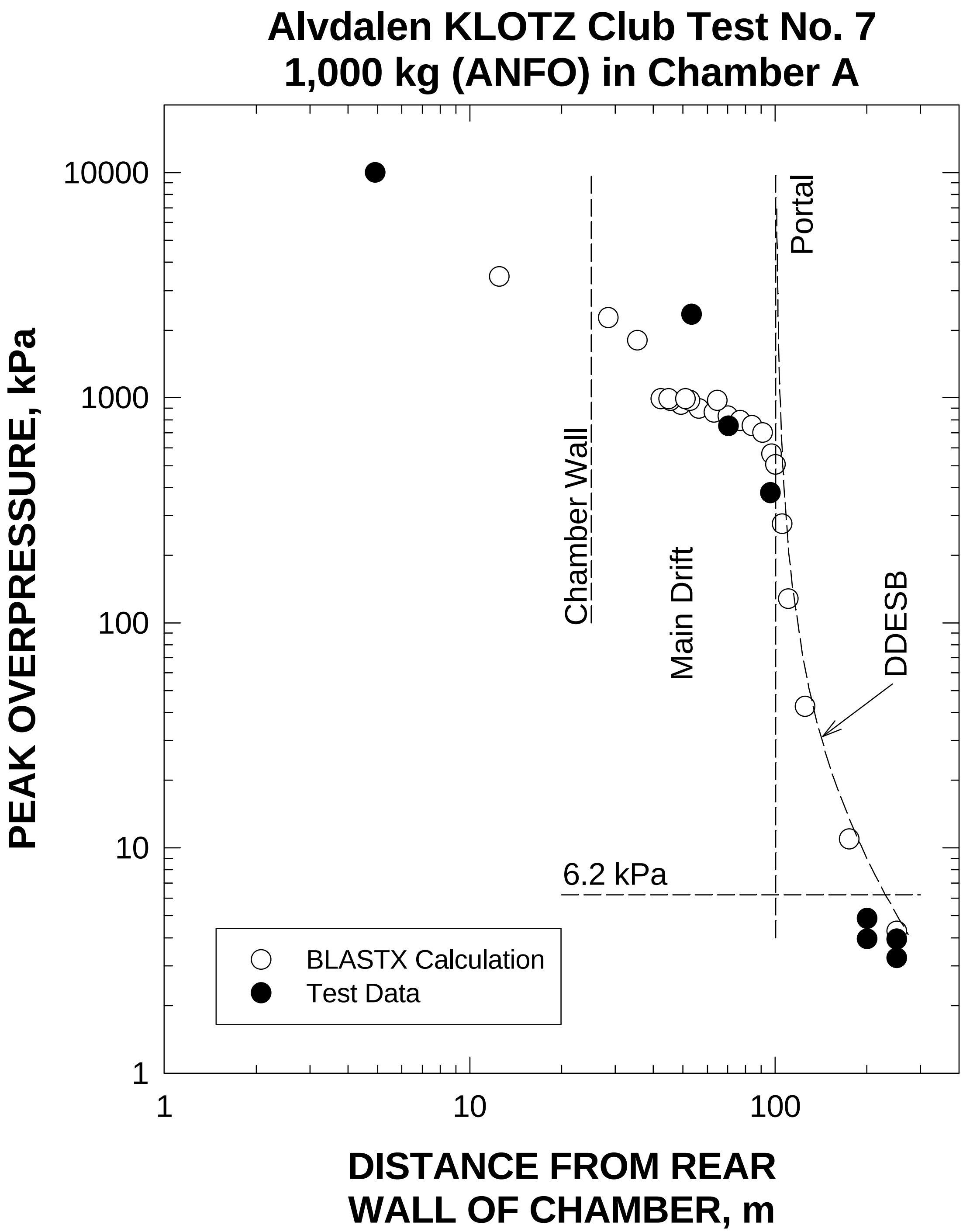


Figure 19. Peak overpressure versus distance fromrear wall of Chamber A. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from KLOTZ Club Test 7.

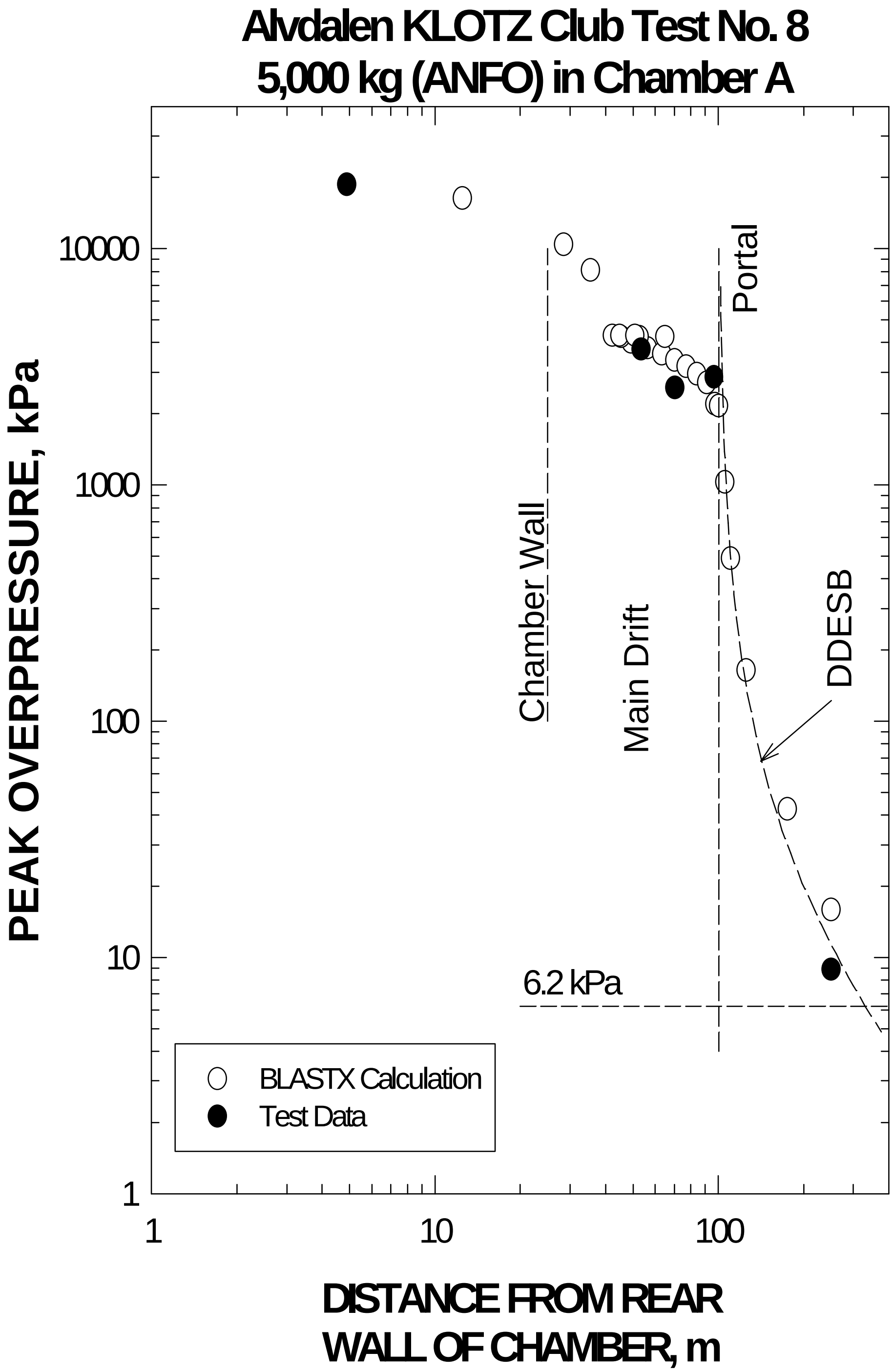


Figure 20. Peak overpressure versus distance from rear wall of Chamber A. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from KLOTZ Club Test 8.

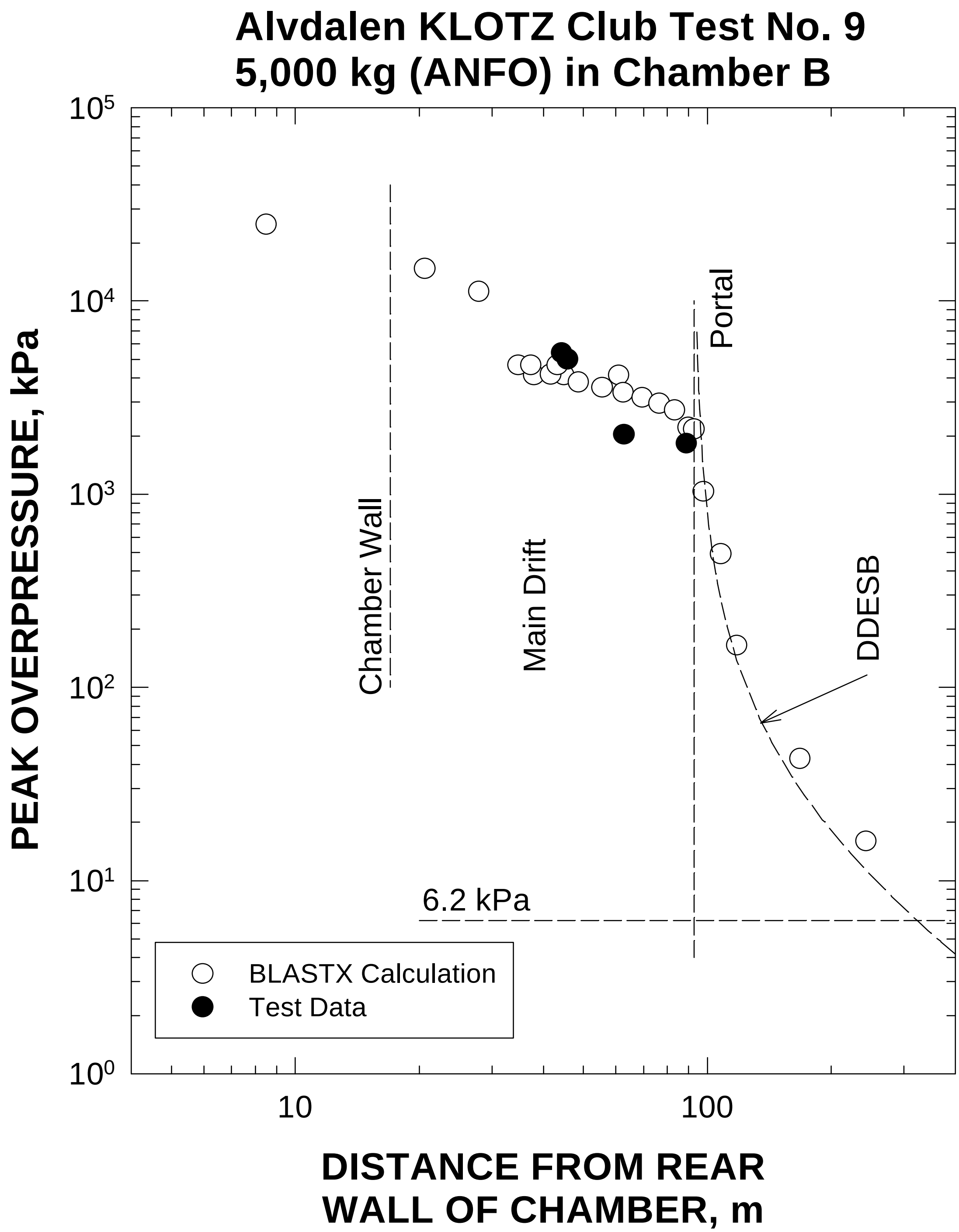


Figure 21. Peak ocerpressure versus distance from rear wall of Chamber B. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from KLOTZ Club Test 9.

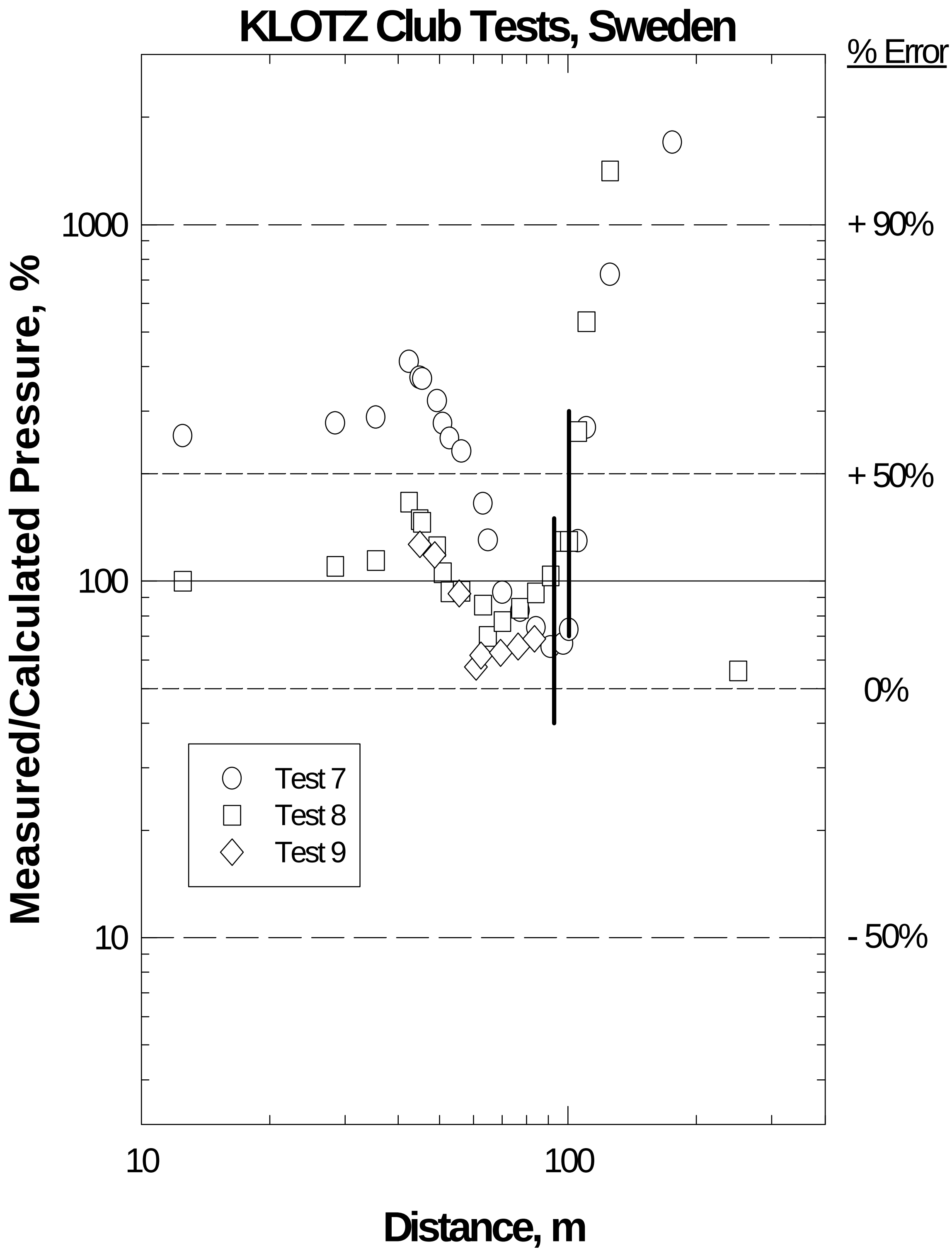


Figure 22. Prediction ratio (measured pressure divided by calculated (BLASTX) values) versus distance for (KLOTZ Club underground magazine tests. (Tests 7, 8, and 9).

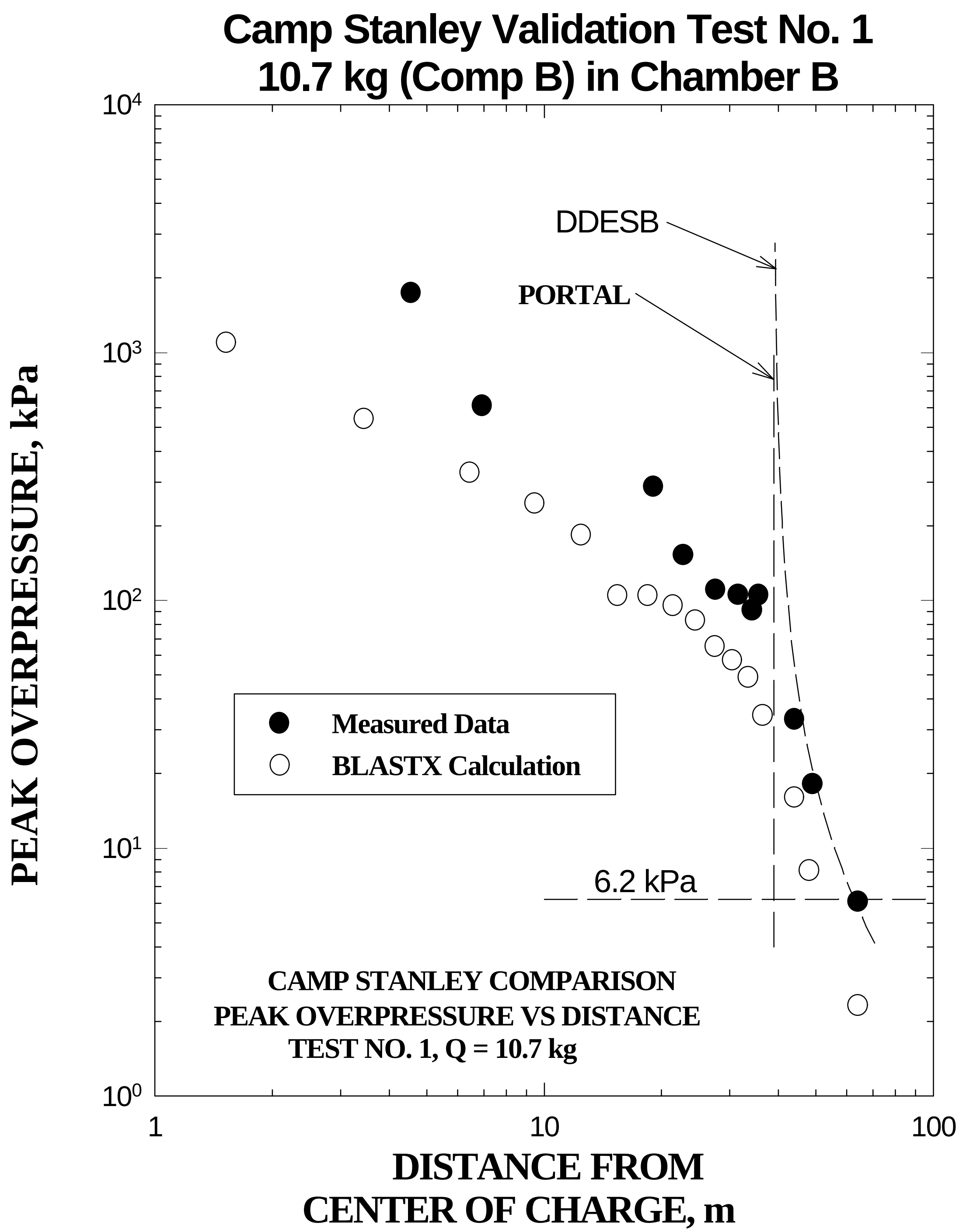


Figure 23. Peak overpressure versus distance from center of charge in donor Chamber B. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Camp Stanley 1/3-Scale Validation Test 1.

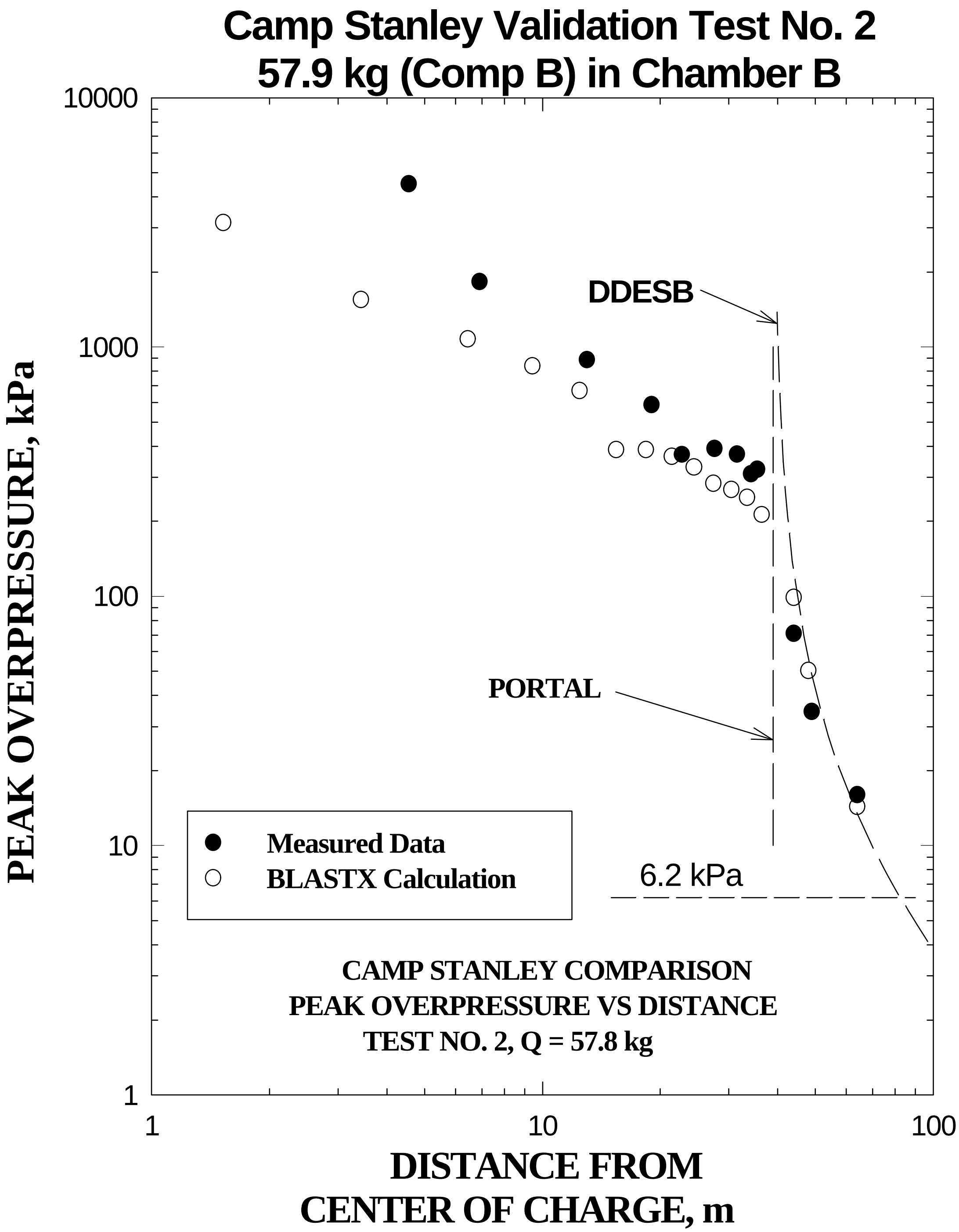


Figure 24. Peak overpressure versus distance from center of charge in donor Chamber B. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Canp Stanley 1/3-Scale Validation Test 2.

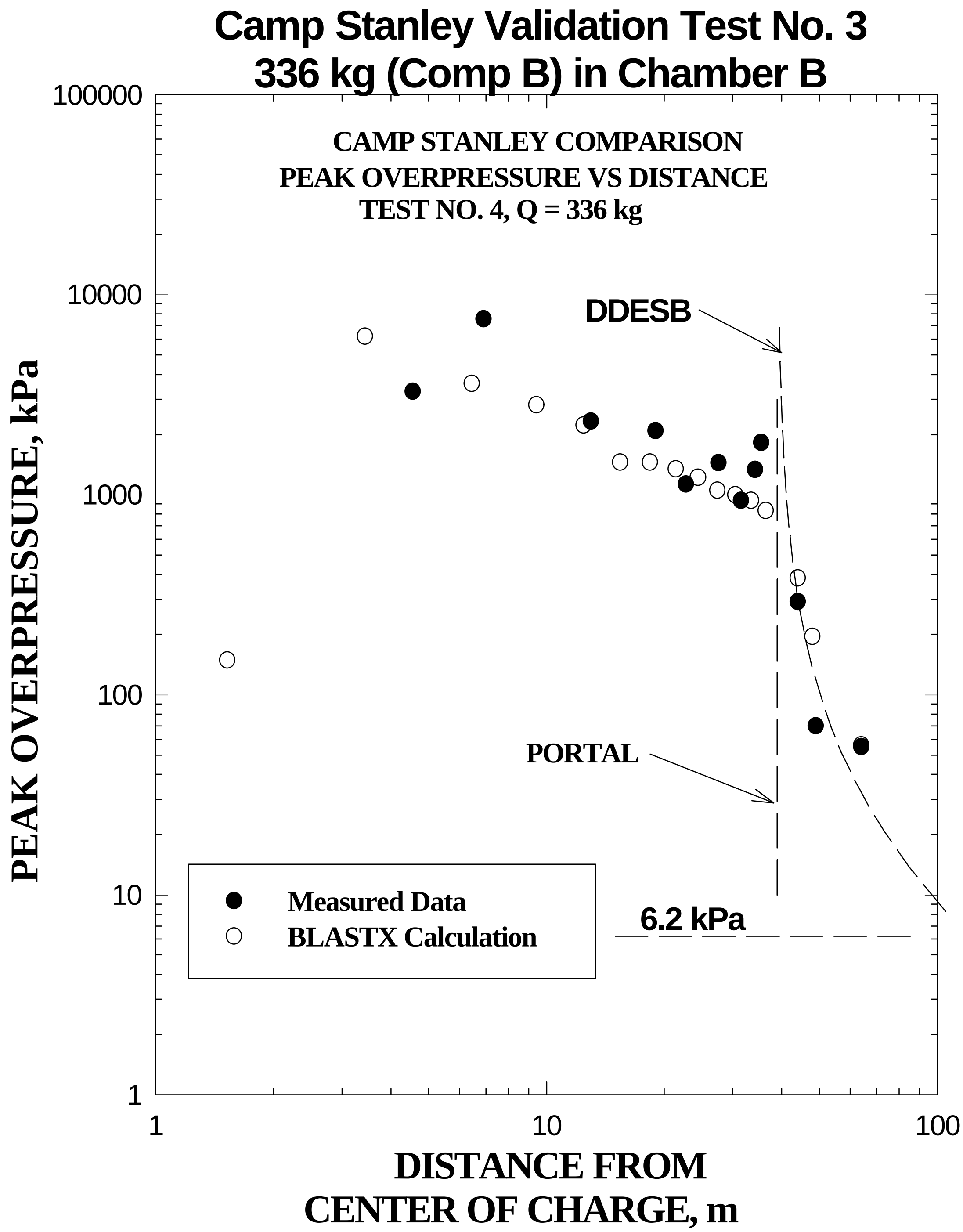


Figure 25. Peak overpressure versus distance from center of charge in donor Chamber B. Comparison of measured and calculated (BLASTX and revised DDESB criteria) data from Camp Stanley 1/3-Scale Validation Test 3.

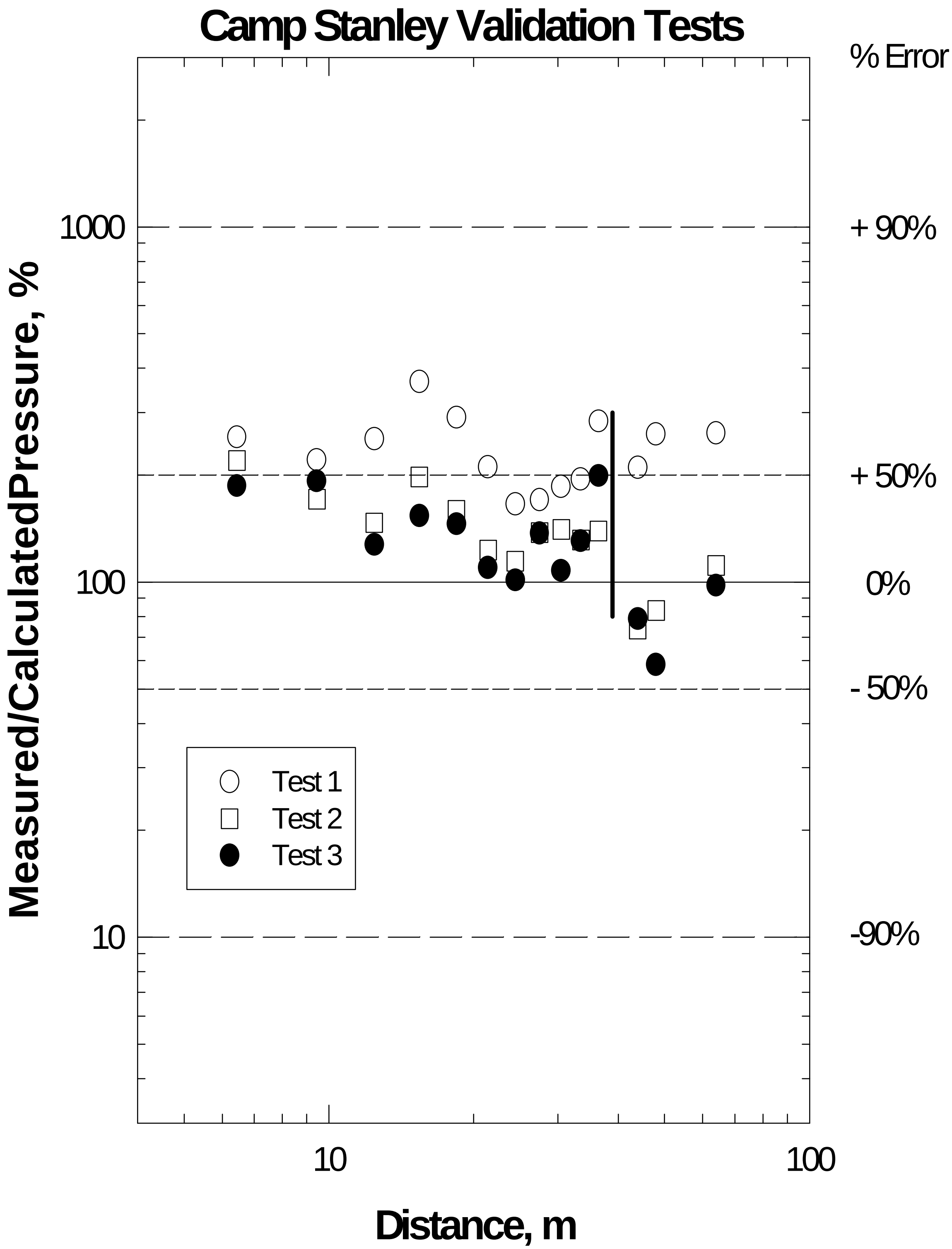


Figure 26. Prediction ratio (measured divided by calculated (BLASTX) value) versus distance for the Camp Stanley 1/3-Scale Validation Tests (Tests 1, 2, and 3).